UTILITIES ON PERMANENT SNOWFIELDS

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PREFACE

This monograph was prepared by Malcolm Mellor, Research Civil Engineer, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory (USA CRREL). It is the fourth in a series of five monographs on *Snow Engineering: Construction*. They summarize many years of development in site studies, laboratory work, and excavation and construction techniques almost entirely the work of USA CRREL.

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EDITOR'S FOREWORD

Cold Regions Science and Engineering consists of a series of monographs written by specialists to summarize existing knowledge and provide selected references on the cold regions, defined here as those areas of the earth where operational difficulties due to freezing temperatures may occur.

Sections of the work are being published as they become ready, not necessarily in numerical order but fitting into this plan, which may be amended as the work proceeds:

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F.J. SANGER

UTILITIES ON PERMANENT SNOWFIELDS

by

Malcolm Mellor

WATER SUPPLY AND WASTE DISPOSAL

Water Supply

On permanent snowfields there is no shortage of high quality water. It is, in fact, the only local commodity. The problem is that it exists almost entirely in the form of snow and ice. In certain regions there are deep meltwater ponds and lakes which may retain an unfrozen core of water through the winter, but these are rarities when the vast expanses of Greenland and Antarctica are considered. For all practical purposes it must be assumed that water will have to be produced by melting snow or ice when facilities are established on ice caps and ice shelves.

Energy for water production

The energy demands for melting snow and ice are very heavy. The latent heat of fusion for ice is 79.7 cal/g, or 144 Btu/lb. The specific heat is approximately 0.5 cal/g or 0.5 Btu/lb. Thus the total heat required to produce water from snow or ice, Q_p, is:

$$\left. \begin{aligned} Q_p &= 79.7 + 0.5\,\Delta\theta_C \ \text{cal/g} \\[1em] &= 144 + 0.5\,\Delta\theta_F \ \text{Btu/lb} \end{aligned} \right\} \tag{1}$$

where $\Delta\theta_C$ and $\Delta\theta_F$ are the temperature difference (in degrees C and F respectively) between the original snow or ice and the final water.

It is evident that water production by independent melting is bound to be expensive. Typical liquid fuels* have calorific values of approximately 20,000 Btu/lb, so that even with perfect efficiency the production ratio would be around 120 lb of water per lb of fuel burned. A more realistic figure for even the most efficient practical melting system would be about half this value – say 60 lb water per lb of fuel, and 25 lb water per lb of fuel is good for a snow tank melter.[45] The cost of fuel delivered to remote sites in the polar regions might easily reach \$5/gal, so that the cost of water production, excluding labor and equipment, could be 5¢ to 10¢/gal in an independently heated melting operation. Thus strenuous efforts must be made to find and utilize cheap sources of energy for snow melting.

The obvious natural source of energy for snow and ice melting is solar radiation. In the polar regions, the global radiation on a horizontal surface during summertime can be up to about 1000 cal/cm²-day. Assuming that all this radiation could be absorbed without loss (or assuming

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*Arctic diesel fuel ≈ 19,500 Btu/lb
Kerosene   ≈ 20,000 ''
Gasoline   ≈ 20,500 ''
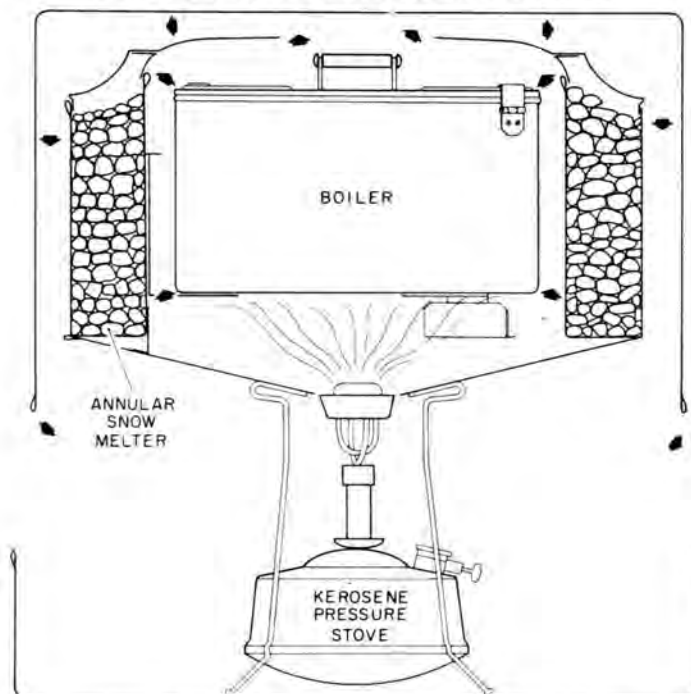
*Figure 1. The Nansen cooking pot and snow melter illustrates
a basic principle of ice cap water supply - use waste heat to
the full.*

losses could be roughly compensated by tracking the sun with the absorbing surface), each square meter of receiver surface theoretically could provide enough heat to produce something on the order of 10 liters of water per day, i.e. 1 yd^2 could provide the heat for up to 2¼ gallons of water per day in summertime. As far as is known, solar radiation has never been used for systematic water production* at ice installations, but simple calculations suggest that solar melting might be feasible in summertime, which is the season when water demands tend to rise due to the influx of visitors and temporary workers.

There is also an unlimited amount of energy available in the winds which are so prevalent at most ice cap sites. It is technically possible to utilize this energy for snow melting via wind generators. However, it would be desirable to design the system for efficient operation since the energy input fluctuates with time.[26]

A more consistent source of cheap energy can be found in waste heat from power plants, heated buildings, and other heat-producing equipment. This rejected heat is so abundant in typical installations that there is a good deal more than is needed for normal water production. No designer can afford to ignore this heat, for it represents a definite liability if it is not disposed of in a carefully controlled manner. Typical sources of waste heat are engine exhausts, engine coolants, air exhausted from heated buildings, and large assemblages of electronic equipment. In general, heat from high temperature sources such as engine exhausts and coolants is easier to recover than that from low temperature sources.

In typical diesel-electric power plants, less than 30% of the energy supplied by the fuel is delivered as electrical energy, even when the set is operating near peak efficiency. Near full-load

*During a summer sledging journey the writer produced drinking water, for three men, in blackened containers exposed to the sun.
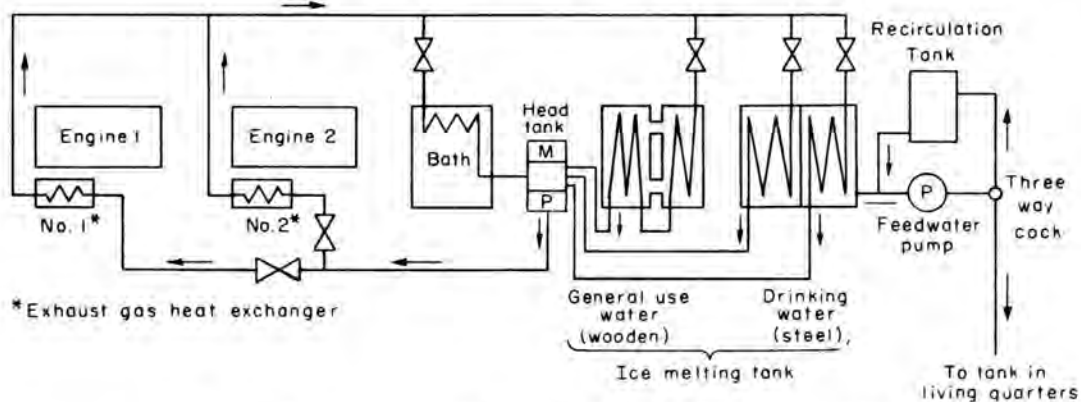
(a) *The final arrangement of the water-making equipment (1962).*
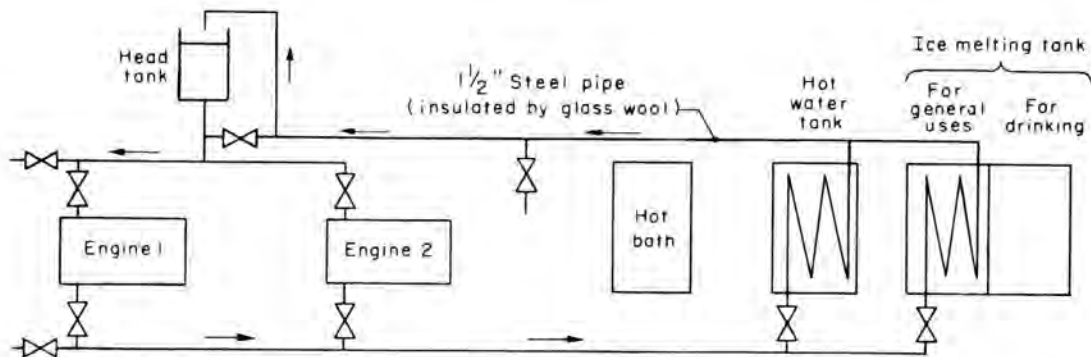
(b) *System for recovery of engine coolant heat for melting snow and for heating water.*

Figure 2. *Snow melting equipment designed for Syowa Base, Antarctica. (Awano and Maita[4])*

conditions, something over 35% of the heat supplied by the fuel appears as exhaust heat, while 20% to 25% is given up to the coolant.[4,30] At most installations this represents ample heat for water production.

With a heat recovery system designed for an under-ice camp in Greenland, Russell[30] was able to utilize, over a prolonged period, 43% of the heat supplied by generator fuels for water production, domestic water heating, and space heating. Water production accounted for 38% of the input fuel heat. With a system (Fig. 2) designed for use at a Japanese Antarctic station, Awano and Maita[4] recovered 88% of the available exhaust heat, or 33% of the heat supplied by the fuel at full load. Another system for recovery of coolant heat was capable of utilizing 56% of the coolant heat, or 14% of the heat supplied by the fuel at full load. These tests prove that diesel power plants can provide "free" heat amounting to better than 40% of the calorific value of the fuel burned in the engines.

Water consumption rates

In order to design a water supply system it is necessary to estimate rates of water consumption. These rates depend chiefly on the number of men using the station and the extent to which bathing, laundry and sewer facilities are provided.

The absolute minimum water requirement for a primitive temporary camp or an oversnow train can be set at 2 gal/man-day, 1 gallon each for drinking and cooking. A more reasonable figure for a temporary camp might be 5 gal/man-day, which allows for some bathing and laundry. The minimum consumption for a simple permanent station might be 10 gal/man-day, and per capita rates for more elaborate stations escalate from this base. By polar standards, 50 gal/man-day is a generous water allowance; this is enough to provide for adequate bathing, laundry, and sewage transport, assuming that the users behave responsibly. If there is unlimited access to showers, flush toilets, and washing machines in a large station, where some irresponsible usage can be expected, the rate of consumption can rise even further, but 100 gal/man-day can be taken as a ceiling.

At some stations there appears to be a significant fluctuation in per capita water consumption between winter and summer. In Antarctica, winter rates of 10 gal/man-day have been reported against summer rates of 20 to 30 gal/man-day.

The significant point is that per capita consumption can vary over an order of magnitude, so that there is ample scope for effecting economies. Since water is an expensive commodity at a polar station, there is a strong case for designing economy and self-regulation into the water use system. For example, water demands can be cut down significantly by fitting special shower heads and flush toilets, and by recycling used wash-water for use in toilets.

Water quality and treatment

Providing there has been no contamination from human activity in the area, virtually all snow and ice in the ice caps and ice shelves of Greenland and Antarctica yields excellent potable water. Except for snow which has been exposed to salt spray from the ocean or to products of human activity, ion concentrations for the common impurities are almost always less than 1 mg/liter (see CRSE Monograph III-A1, Chapter I). An indication of the high degree of purity is given by the electrical conductivity of meltwater from central Greenland and Antarctica—typically 1.5×10^{-6} mho/cm as measured at 20 to 25C.* Snow meltwater is quite acidic; typical pH values for ice cap snows are from 5.0 to 6.0, which is generally below the desirable minimum of 6.0. There are normally no detectable coliform bacteria in ice cap snow, although it is possible for a variety of microorganisms to live, grow and multiply on the surface of snow when light is plentiful and temperatures are at or near the melting point (see Monograph III-A1). Unless there is snow-free terrain upwind of the area, the concentration of solid impurities in polar snow is completely negligible.

If snow is handled and melted properly it can be expected to yield water of very high quality, and no treatment is required for domestic use. At many polar bases, meltwater has been used without any form of treatment. However, at some large stations the water supply becomes contaminated during production and distribution. At U.S. military bases in Greenland the water is chlorinated to about 1 ppm to counteract possible biological contamination during storage and distribution. The water derived from surface snow at some stations in Antarctica is fouled by fuel, lubricants, soot, and other exhaust products. It is treated by filtering through diatomaceous earth or charcoal, and in some cases baking soda is added to combat oily tastes. It would seem preferable to pay more attention to the design and operation of water systems so that gross contamination is avoided.

For certain special water uses, in which corrosion is a potential problem, it may be necessary to adjust the pH value upward by adding, for example, calcium carbonate.

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*Clark[10] quotes values from 1.2×10^{-7} to 1.7×10^{-7} mho/cm for water from the Camp Century well. Unless special precautions were taken to exclude carbon dioxide, these values seem anomalous.

The human propensity for fouling the environment can have serious consequences at ice cap sites, since there is no practical way of purging the snow once it has been contaminated. Hence it is important that some sector of the site should be kept free from sewage disposal, trash dumping, and all unnecessary activities. The upwind sector is the obvious area for designation as a clean zone.

Techniques and equipment for melting snow and ice

There are two broad approaches to snow-melting: the snow can be collected mechanically and transferred to a tank for melting, or snow and ice can be melted *in situ* and ponded in impermeable strata. A big advantage of the latter method is that it reduces mechanical handling and thus limits the possibilities for contamination. With both methods the necessary energy can be supplied either by an independent power source or by a heat reclaiming system.

A *tank melter* consists basically of a large enclosed container located close to the heat source, with some type of hopper, chute, or conveyor for loading snow from the outside. Snow is harvested from a clean collecting area and is fed to the loading hopper by hand, front-end loader, dragline, or some other means. If there is no clean snow close to the melter, as is often the case, snow has to be hauled in by sled or other vehicle from more distant collecting areas. Heat is
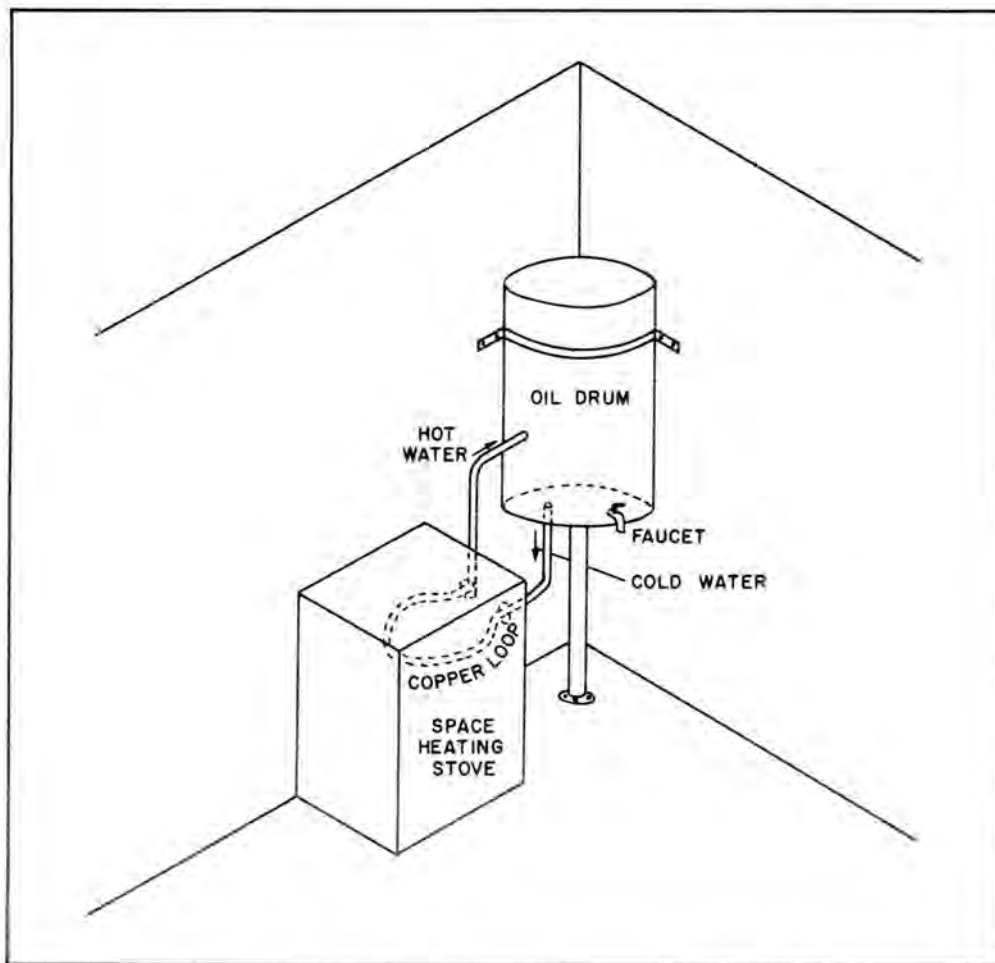
Figure 3. Improvised thermo-siphon melter/heater for small buildings.
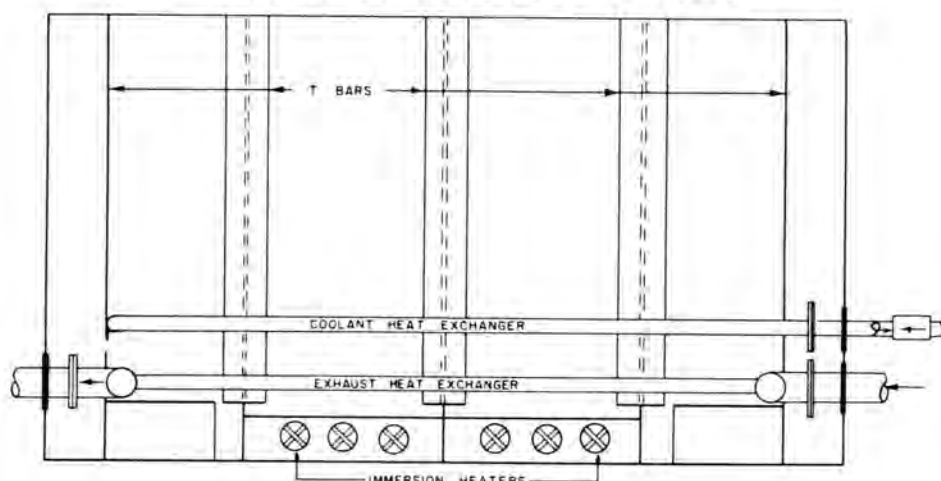
Figure 4. Schematic cross section of U.S. Navy Mark III waste-heat snow-melter. This melter is designed to produce an average of 145 gal/hr when connected to a 50-kw generator and loaded by one man. (Tinklepaugh.[12]) (No dimensions were given in the cited report. Pipes were 1½ in. diam and the tank was apparently about 4 ft square in plan. An efficiency of 72% was computed from observed data.)

transferred to the snow in the tank in various ways, e.g. by closed immersion tubes conveying hot gases, by closed immersion tubes conveying hot liquids, by electrical immersion heaters, by water circulation through an external heater, or by overhead hot water sprays.

Snow melting tanks should be designed and maintained to avoid accidental entry of contaminants. The tank should be completely enclosed, and precautions should be taken against leakage of gases or poisonous liquids (e.g. antifreeze) from immersed heating coils.

Some high-capacity melting tanks with independent heating have been adapted for polar use from commercial asphalt melters. Arctic diesel fuel (basically kerosene) is favored for heating purposes, since it burns efficiently and is the standard fuel for heavy vehicles and stationary engines. Oil-fired domestic water heaters have been converted to convenient snow melters; water is drawn from the melter tank, heated by a gun-type burner, and returned to the tank.[17][37]

Heat reclaiming systems fitted to diesel generators must be designed in such a way that the performance of the engine is not affected adversely.

In principle, the thermal efficiency of melters can be very high. In practice, it is found that flame-heated melters usually manage a heat recovery in the range 40% to 70%, although recovery rates in excess of 80% are attainable under favorable circumstances. Figure 4 shows an efficient waste-heat snow melter.

In recent years a variety of large snow melters have been developed for disposing of snow plowed from city streets. Their melting capacities range from 25 to 100 tons/hour. Thermal efficiencies exceeding 90% have been claimed by manufacturers, but these claims are likely to be exaggerated.

Any kind of snow-melting equipment should be thermally isolated from its foundations, or from those of the building in which it is housed. If the melter is in a snow tunnel, the transfer of heat to walls and roof should be limited as far as possible. Precautions should be taken against water leakage, as even a slow drip can play havoc with snow foundations.

ICE CAP SURFACE

Ceiling

TRENCH

Floor

Pump Water Line

Steam Line

STEAM GENERATOR

WATER STORAGE TANK

"A" FRAME and WINCH CABLE ASSEMBLY

PUMP SUSPENSION CABLE

WATER LEVEL

MELTING-PUMP BIT ASSEMBLY
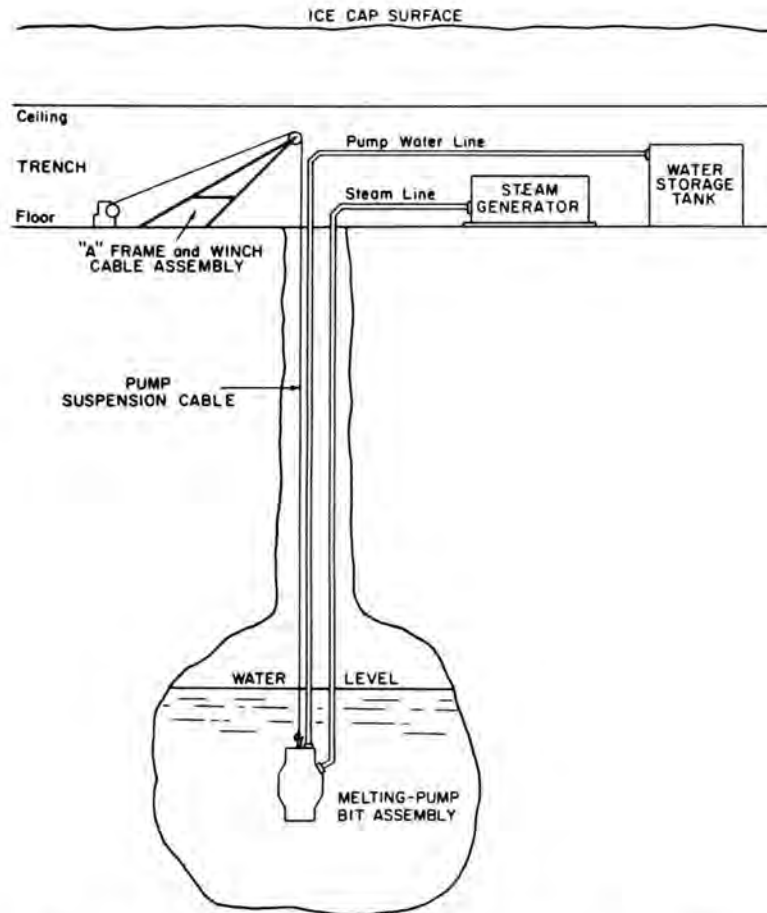
Figure 5. Camp Century water well equipment. (Clark.[10])

A formidable bulk volume of snow has to be handled during the loading of melters. The density of undisturbed surface snow on ice caps is usually between 0.2 and 0.4 g/cm^3 (12.5 to 25 lb/ft^3) and further bulking occurs when the snow is dug out. The overall bulk of the snow loaded into a melter may be ten times the volume of the meltwater produced.

In-situ melting in water wells was developed in Greenland for providing water supply to large military camps[10][33][34] (Fig. 5, 6, 7, 8). Snow or ice is melted and stored in place at a considerable depth below the ice cap surface, thus eliminating the need for mechanical handling of snow and for imported storage tanks.

A hole is driven down into the snow, preferably by hotpoint boring or steaming, and vertical advance is maintained until impermeable strata are intercepted, or until refreezing meltwater forms its own impermeable barrier. Ponding of the melt then occurs and, after sufficient reserve capacity has been established in the well, pumping can begin. Subsequent development of the ponding cavity in size and shape depends on the relative rates of melting and water removal by pumping, and also upon the pattern of heat application in the pool: with a large heat supply and small pumping rate the cavity grows laterally as well as vertically, but if the pool is over-pumped the cavity tends to develop downward as a relatively narrow hole.
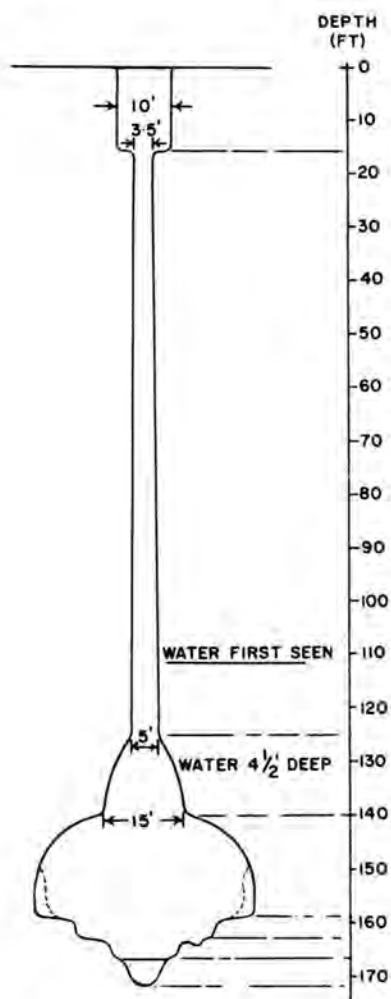
Figure 6. Section of the pilot water well at Camp Century after the first test season. (Schmitt and Rodriguez.[34])
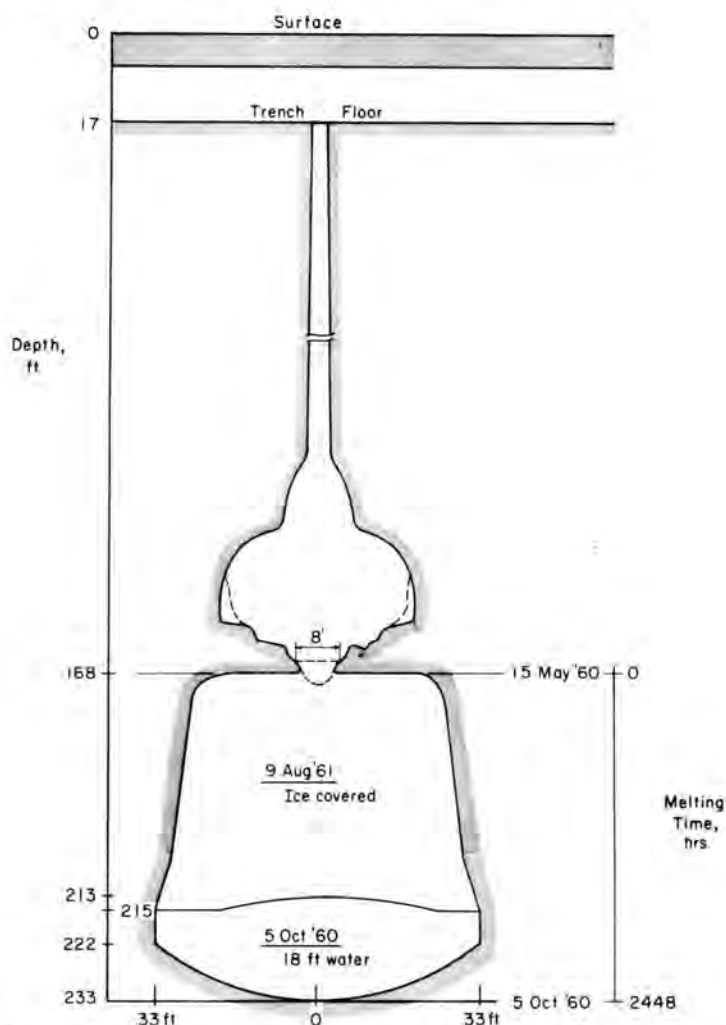
Figure 7. Section of the Camp Century water well after two seasons of operation. (Schmitt and Rodriguez.[34])

On the ice cap in northern Greenland, initial ponding of the meltwater occurs at depths between 120 and 150 ft. If heat is supplied to a central point at the base of the shaft, the pool first forms a radially symmetric equant cavity, which later develops in response to the pattern of heating and pumping. While the cavity is small, heat losses by conduction through the surrounding ice and by convection in the air above are quite insignificant. As the pool grows the heat losses increase, until finally an equilibrium size can be reached, at which stage all of the heat input is lost by conduction and convection and no new water can be produced unless the rate of heat supply is stepped up. A detailed analysis of heat conduction to the ice surrounding an idealized spherical well cavity has been given by Tien,[41] who treats the "open loop" system, in which heated fluid is circulated directly through the pool, and the "closed loop" situation, in which heat is transferred to the pool from a heat exchanger loop. Numerical results are given for the very high heat supply rate of 27 million Btu/hr (the analysis was actually concerned with heat sinks for power plant cooling,

FLOOR of ICE DRIFT

Volume Calculated as a Paraboloid Figure.

$$\left(\frac{\pi\, r^2 h}{2}\right) 7.48 = \text{Volume in Gallons}$$

Where:
r = Radius at Pool Surface
h = Depth of Water

THIS SECTION HAND DUG

THIS SECTION SUNK by CONTROLLED MELTING & PUMPING

r = 14.5'

Ice Accumulation 10 Oct. 1961 to 20 Feb. 1962

Water Level 20 Feb. 1962   22"
Water Level 28 Feb. 1962

r = 16.9'

NO WATER PRODUCTION THIS PERIOD

Water Level 17 Apr. 1962
Water Level 29 Apr. 1962

r = 15.6'

r = 16.4'

3.5 inches of Ice Measured on 17 July 1962

Water Level 7 June 1962

r = 19.5'

Volume in Reservoir 20 Feb. 1962 = 48,340 Gallons

Water Depth = 18'

Volume 28 Feb. 1962 = 73,600 Gallons

Volume 17 Apr. 1962 = 52,600 Gallons

Water Depth = 22'

Water Depth = 18.4'

New Water Production Started 17 Apr. 1962

Volume 29 Apr. 1962 = 70,500 Gal.
Water Depth = 22.3'

Volume in Storage 7 June 1962 When Water Production Stopped = 108,400 Gallons

Depth From Floor of Drift to Reservoir Bottom 7 June 1962 = 52.52'

Water Depth = 24.15'

Figure 8. Water well development in impermeable ice. Average rate of heat supply approximately 260,000 Btu/hr. (Russell.[30])
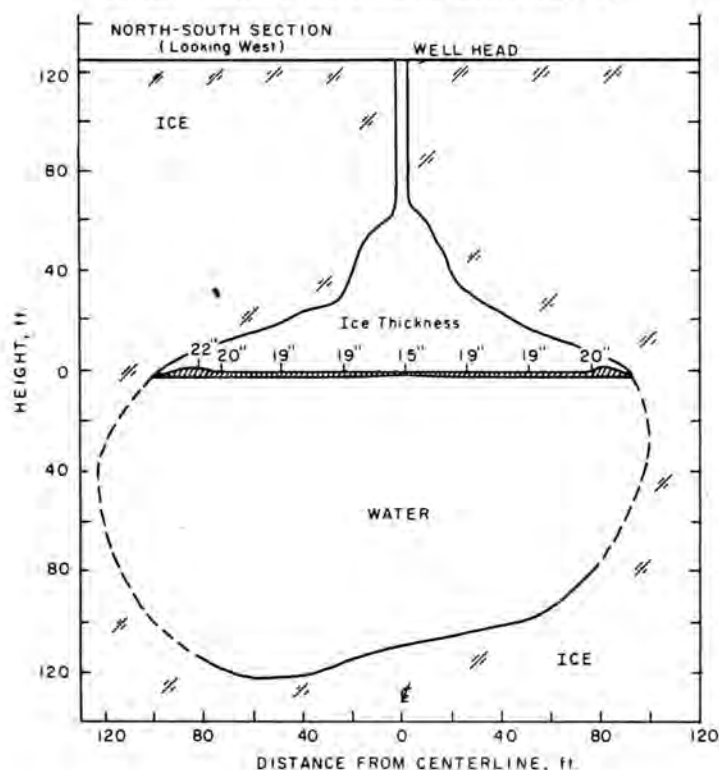
*Figure 9. Water well used as a heat sink for the glycol cool-
ant of a nuclear reactor at Camp Century, Greenland. No
water was removed from the well. (Clark.[10])*

but it is directly applicable to water production wells). Combining observation with analysis for a well in an ice tunnel, Russell[30] gives simplified engineering calculations and results for the relatively small heat input rate of approximately 250,000 Btu/hr. Schmitt and Rodriguez[34] report observations on cavity development in a well supplied with heat at the rate of 750,000 Btu/hr.

At Camp Century a special water well was used as a heat sink for the glycol coolant of the nuclear reactor.[10] No water was removed from this well, and in 2 years of operation about 20 million gallons of water was melted and ponded (Fig. 9).

A water well can compromise the integrity of foundations, excavations, and structures in the overlying and surrounding strata, and for this reason wells should be separated from structures. The maximum cavity radius experienced so far is about 60 ft, but measurable warming of the snow can be expected within a 200-ft radius of the well center. A method for estimating temperature disturbance as a function of radius and time is given by eq 2 (p. 17).

With a steady heat supply and a steady pumping rate, it seems likely that a water well would tend to develop downward at the expense of lateral growth. In doing so it would automatically minimize heat loss, but the pump lift requirements and the line losses would increase. In general, it is probably advantageous to exploit a well by vertical development over some selected range, and then abandon it to start a new well. The dry cavity of an old well might be used for POL storage. If left empty, a well cavity will gradually close by viscous flow of the ice; if there are structures in the vicinity the effects of cavity closure must be taken into consideration.

Water distribution

After production, meltwater is taken into storage tanks or, in the case of wells, stored *in situ*. While in storage, the water must be protected from heat loss by insulation and/or provided with heat to compensate for losses. From the storage point, water may be distributed in a variety of ways, depending on the nature of the establishment.

The required storage capacity may vary considerably according to the nature of the production operation and the water use pattern. If the melting operation is not continuous the storage demands increase. There is also the question of whether or not the water supply is expected to provide some fire protection.

At small or temporary camps the most expedient system may involve only distribution in portable containers, e.g. hand-carried cans or tank sleds. At permanent stations it is preferable to have piped distribution from the central water supply. Piped supply through unheated areas necessitates precautions against freezing in the line; water can be carried through insulated pipes wrapped with electrical heating tape (Fig. 10), using gravity or pressure feed, or else the water can be circulated continuously by pump, through insulated lines and back to the warm storage tank. All plumbing systems should be capable of easy drainage to avoid freezing damage during shutdown periods.

In a dispersed facility, the buildings which have a strong demand for water, such as latrines, laundries, kitchens and messes, are usually grouped close to the main water source. More remote buildings with light water demands are likely to be provided with independent melter systems.
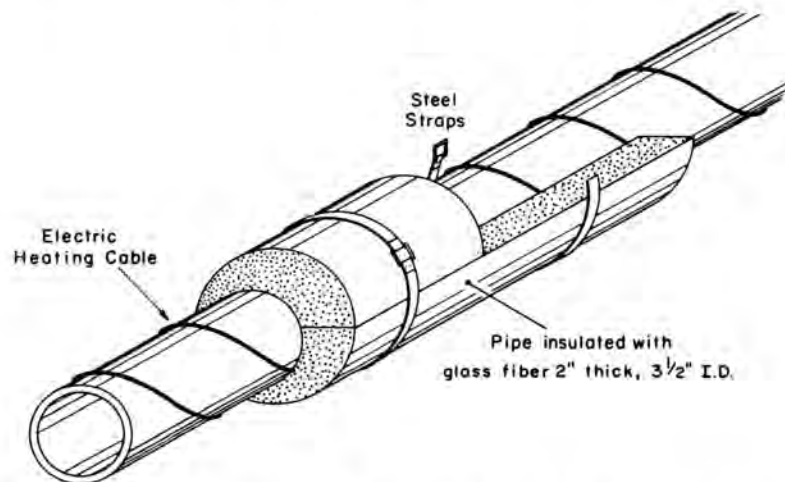
Figure 10. Insulated pipe with electric heating cable wrapping.

Examples of existing water supply systems

Camp Fistclench (Site II), Greenland – basic system.[44] Camp Fistclench, constructed in 1957, was an experimental undersnow camp used only in summer for the development of techniques and criteria later used for Camp Century, the first undersnow camp planned and constructed by the U.S. Army Corps of Engineers for year-round occupation.

Snow was melted in two tanks heated by kerosene burners (arctic diesel fuel). The melters were housed in a roofed trench of the undersnow camp, and were supported on a platform built over nine 6 × 6-in. timber piles and three 4 × 4-in. piles, each pile penetrating 5 ft into the snow. The

loading hopper was accessible from the surface. Snow was hauled in from a collecting area on 10-ton sleds.

The melters were elevated 9½ ft above the trench floor, giving gravity flow to two 1100-gal tanks mounted on timber piles inside a Jamesway hut. Water was piped to the kitchen, showers and latrines in a circulating system driven by two 15 gal/min pumps. Pipes were lagged with standard asbestos insulation. Water was hand-carried to individual quarters in 5-gal cans.

Early sources of contamination were leaks in the melter fire-tubes, fumes and soot from the melter stack (if the tank was left uncovered), and flakes of paint and rust in the hand-carry cans.

Camp Fistclench, Greenland – experimental water well. A second, largely experimental, water supply system was developed at Camp Fistclench. A vertical shaft was steamed down through the snow, which is at a temperature of about –11F in the natural state, and an impermeable barrier was reached or developed about 130 ft down. Meltwater ponded at this level and a chamber was thawed out. Steam was supplied to the well to maintain water level and compensate for heat loss, and water was pumped to the surface for use in the camp.

Camp Century, Greenland.[10] [33] [34] The water requirement for Camp Century was estimated at 10,000 gal/day, and during construction of the camp in 1959 and 1960 the SIPRE water well concept was developed to an operational stage by USA ERDL to meet this demand.

A shaft was steamed down and ponding developed at 140 to 160 ft. A special bit bubbled steam through the pool and also held a submersible electric pump which fed water to the surface at a rate of 25 gal/min. The water contained no detectable coliform bacteria, and was given only a nominal chlorination of 1 ppm. The water was delivered to the surface at an average temperature of 42F.

The steam generator was a coiled water tube flash-type boiler capable of producing about 750,000 Btu/hr and burning fuel oil at a maximum rate of 7 gal/hr. It produced 165 psig saturated steam at 373F at a rate of about 800 lb/hr. The submersible pump had a capacity of 1700 gal/hr pumping from 200-ft depth, and 1020 gal/hr from 500-ft depth. The overall thermal efficiency of the system in the first test period was 74%, and it was calculated that 66 lb of water was produced and made available for each pound of fuel consumed.

Observations on this pilot project led to the conclusion that the 10,000 gal/day peak water requirement of Camp Century could be met by water wells for the expenditure of 1 million Btu/hr of heat.

Figures 6 and 7 show sections through the pilot well at the ends of the first and second test seasons.

The equipment used for the pilot well was transferred into Camp Century without major modification when the station became operational. The first service well was developed to a final depth of about 500 ft and then abandoned, since the pumping limit had been reached. The well produced 3½ million gallons over a 2-year period. A second service well (Fig. 11) reached a depth of about 300 ft and a maximum pool diameter of 100 to 120 ft. It yielded 5 million gallons in 2¼ years.

USAF ice cap radar station N-34.[43] The water supply of this undersnow station was provided by an independently heated melting tank. Snow was bladed into a 5-ft-diam chute, which passed it into the melting tank. Fire tubes passed through the melter, and warm water was sprayed over the snow from header tubes above. With two of the three burners in action and with good spraying, the melter produced water at a rate of 450 gal/hr. The meltwater was passed to a 1780-gal storage tank, which held about a 4½-day supply for the 20-man establishment. After a period of use the melter tank could be left full to give an additional 4-day supply, refreezing being prevented by the heat of a nearby generating plant.
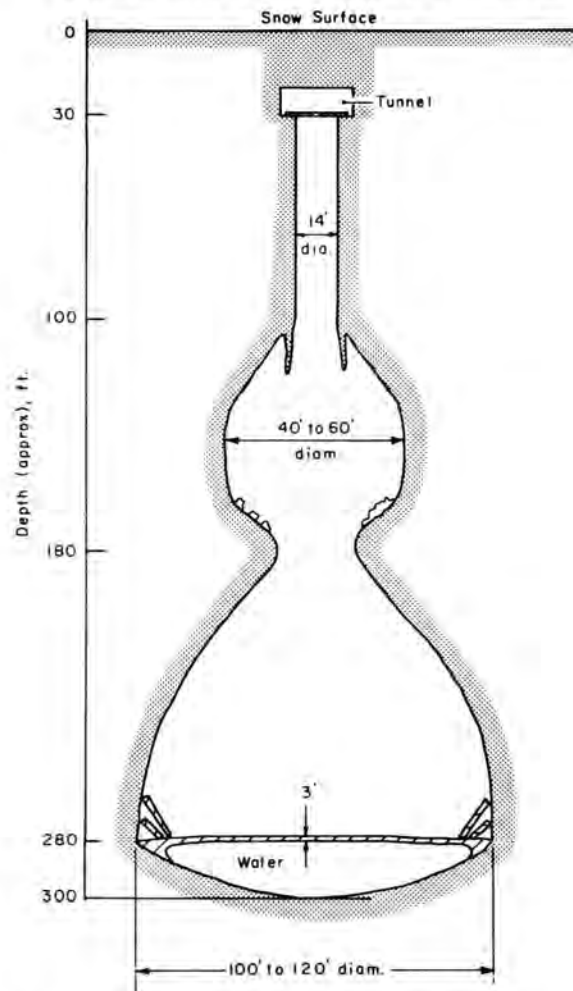
Figure 11. Second service well at Camp Century after 2 years of operation (measured by W. Tobiasson, CRREL, 10 April 1964).

A hydropneumatic pump took water from the storage tank and forced it into a 42-gal tank containing air under pressure. Feed into the pressure tank was automatically cut off at 40 psig. This pressure tank provided the necessary pressure for the distribution lines and faucets. The distribution lines were copper pipes wrapped spirally with 0.5 ohm/ft heating wire and insulated with a 4-in. thickness of hair felt. The pipe temperature was thermostatically controlled at 40F.

Ice cap radar stations DYE 2 and DYE 3, Greenland. Water supply at these stations, which are elevated 19 ft above the snow on columns, is provided by heat exchange melters. Snow is hauled up to the building by remote control, using a fixed dragline which tips into a projecting hopper. Once inside the melting tank (5 × 9 × 6 ft), the snow is sprayed with warm water from nozzles which have a total capacity of 50 gal/min. The spray water is heated by waste heat from the generating engines, using an exchanger. A recirculating pump takes water from the tank, through the heat exchanger, and back to the sprays. A transfer pump takes usable water from the tank for distribution inside the heated composite building by a hydropneumatic system. The system meets the needs of approximately 30 men. It produces about 2000 gal/day, and water consumption runs as high as 60 gal/man-day.

Little America V, Ross Ice Shelf, Antarctica. Snow melters were installed in the powerhouse, the latrine buildings, and the galley. Snow was shoveled manually through a hopper and melted in the tank by circulating warm water, finally being pumped into an overhead storage tank. The powerhouse melter utilized waste heat from the exhausts of the diesel generators and the other melters were independently heated. There was a limited pipe distribution inside the heated buildings.

Similar systems were used at Byrd, South Pole and Ellsworth IGY Stations.

"New" Byrd Station, Antarctica. Snow is collected from an area about ¼ mile upwind of the station and carted by sled to the melter, where the tank is loaded by an inclined conveyor belt. A heat exchanger on the cooling system of the diesel generators provides the energy for melting. The meltwater is filtered through diatomaceous earth, and distributed from a loop in which continuous circulation is maintained providing from 20 to 30 gal/man-day in summer and about 10 gal/man-day in winter. The pipeline is insulated with 2 in. of glass fiber and wound with electrical heating tape where it passes between heated buildings, and is exposed to the heat inside warm buildings. A water well similar to the Camp Century system is planned.

South Pole Station, Antarctica. Two melting tanks are heated by exhaust gases from the diesel generators. Limited pipe distribution is by gravity feed from storage tanks to subsidiary use tanks. There is a steep fall on the uninsulated pipes, which are drained when not in use. Drinking water is filtered through diatomaceous earth and is treated with baking soda to combat an oily taste. Average water consumption is now estimated as 50 gal/man-day, compared with earlier estimates of 20 to 30 gal/man-day in summer and 10 gal/man-day in winter.

NCEL camp, Ross Ice Shelf, Antarctica.[17] This small camp, requiring 12 gal/man-day for about 20 men, was originally fitted with an electrical immersion heater system for snow melting. The electrical system was judged to be unsatisfactory, although the published test data show it to have been extremely efficient. A new system was built in which water from the melter tank was circulated through an oil-fired water heater and returned to the melter reservoir (Fig. 12). The meltwater was filtered through a particle filter and an activated charcoal filter.

Tuto under-ice camp, Greenland. This camp was built inside a complex of tunnels mined into the margin of the Greenland Ice Cap. Water was melted *in situ* at a shallow depth below the floor of a tunnel by continuous circulation of water from the well and through heat exchangers fitted to
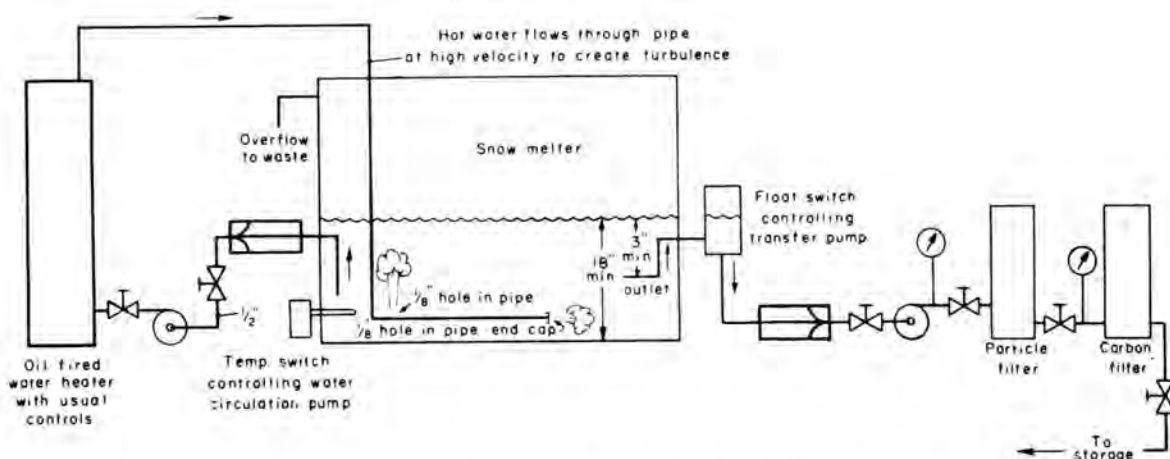
Figure 12. Hot water snow-melter system at NCEL camp, Antarctica. (Hoffmann and Sherwood.[17]*)*
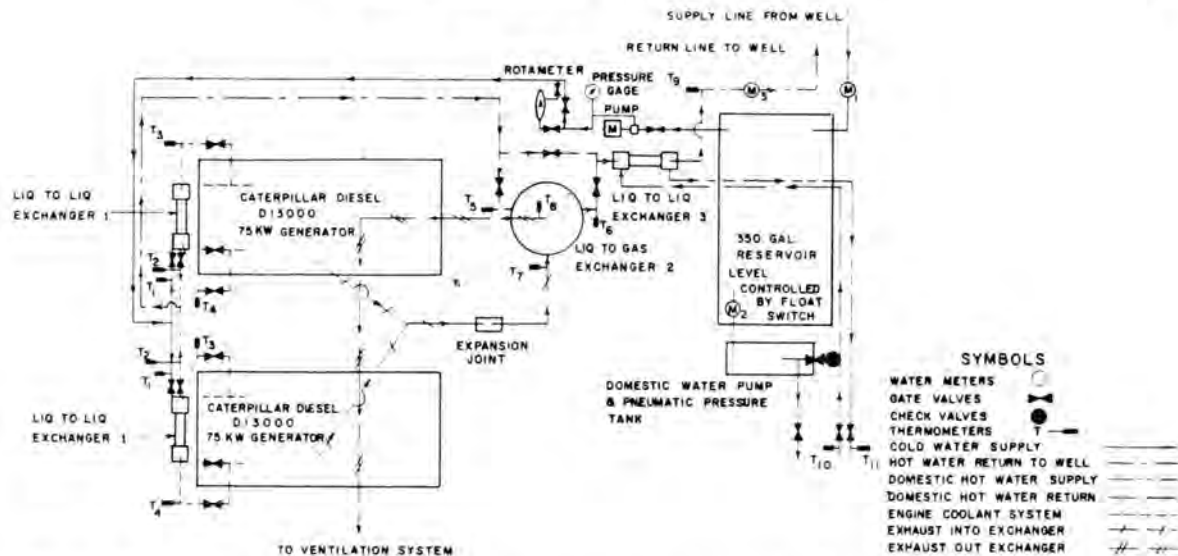
Figure 13. Schematic flow diagram of heat exchange system in the Tuto under-ice camp, Greenland. (Russell.[30])

the station power plants. Heat reclaimed from the generator sets provided water heating and a certain amount of space heating, as well as enough heat to melt ice at a rate two to three times as high as the rate of water consumption. The system is outlined in Figure 13.

Waste Disposal

The wastes at camps on polar snowfields can be classed under four main headings: sewage (waste water, human wastes), garbage (organic kitchen refuse), trash and scrap (non-decaying, inoffensive rubbish), and special wastes (e.g. radioactive wastes).

Sewage is dealt with by hydraulic disposal or mechanical removal, followed by dumping or burning. Garbage is removed either mechanically or by hydraulic discharge after comminution. Trash is simply burned or buried. The disposal of such matter as radioactive waste requires special consideration for each case; waste with a high radiation level will probably be packed in lead or concrete cases for shipment to a designated disposal area, and matter with a low radiation level may be disposed of in the ice cap close to the base.

Sewage disposal on polar snowfields is simplified by the small size and isolation of the community, by the absence of insects and rodents, and by the possibility of arresting bacterial activity by freezing. Conventional sewage treatment is both unnecessary and impractical in most cases. However, dumping in the ice cap must be strictly controlled if future water supplies are to be safeguarded.

Current waste disposal practice is outlined below.

Sewage and sewage sinks

The favored method for disposing of sewage at ice cap installations is piped hydraulic discharge to a sewage sink. The alternatives to discharge into sinks are surface dumping and burning.
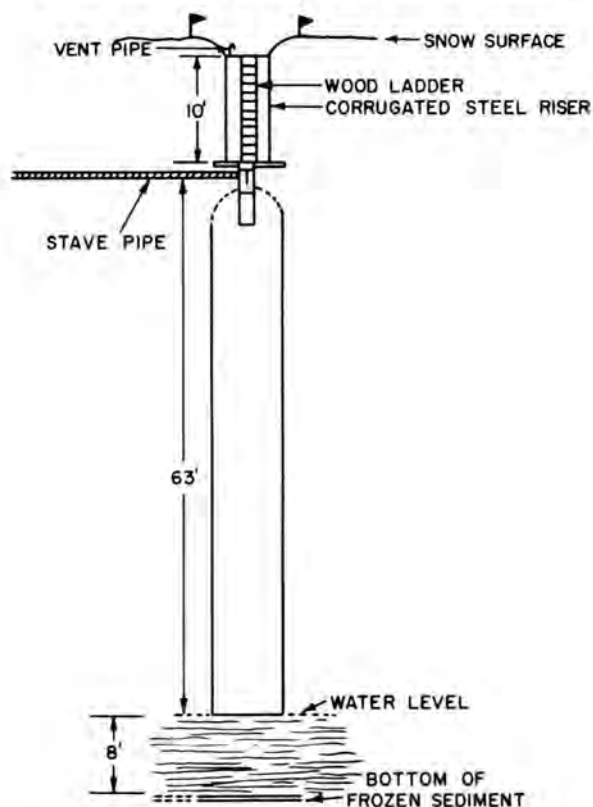
*Figure 14. Original experimental sewage sink
at Camp Fistclench (Site 2), Greenland. (Bader
and Small.[5])*

Dumping involves carrying sewage containers to a disposal area, and is not very effective because of the residual liquids which still have to be dealt with.

Sewage sinks are deep shafts which have been melted down to a depth where the snow becomes impermeable to liquid seepage. If a high rate of initial discharge is maintained, the sewage will penetrate down to the impermeable snow level before dispersing laterally, but with low initial discharge rates the sewage will percolate into the snow and freeze at shallower depths.

Snow becomes impermeable to air when it reaches a density of about 0.8 g/cm³, but observations on actual sewage sinks indicate that cold snow is effectively impermeable to liquid wastes at a density of about 0.75 g/cm³. Snow of this density has been encountered at depths between 100 and 170 ft in Greenland and between 100 and 250 ft in Antarctica; in warm, wet snowfields 0.75 g/cm³ density snow is found at very shallow depths.

Investigations on Greenland sewage sinks show ponding at depths between 70 and 130 ft (Fig. 14). **Ponding** higher than the 100-ft level probably results from a low initial discharge rate or from the presence of impervious ice layers. For design purposes it can be assumed that sewage will pond at the level where snow of density 0.75 g/cm³ is encountered. This depth is found from the depth-density curve for the site.

At the base of a sewage shaft the liquids diffuse laterally by seepage through the pores of the snow, usually melting the snow into a slurry in the process. Initially the base of the contaminated zone is horizontal, in conformity with the impermeable stratum, but in general the zone of active

seepage and melting has a discoid shape. It is found that for given conditions of sewage discharge rate, site temperature, and snow type, the sewage lens reaches a fairly constant overall diameter. The zone of contamination then builds up as a cylinder of refrozen snow and sewage with a wet discoid cap of sewage from the current input.[2b]

The storage capacity of the snow before infiltration is indicated by its porosity, since the inflowing sewage has to occupy the void spaces in the original snow. If, as observations suggest, the radius of the contaminated zone is constant for a given sewage sink, this radius can be related to the rate of sewage input and the rise in sewage level in the central shaft.[3] If it is assumed that the contaminated zone develops upward as a cylinder,* the rate of change of sewage volume with cylinder height, dV/dh, is approximately (ignoring curvature of the top) $n\pi R^2$, where n is porosity of the original snow and R is the radius of the contaminated zone. Thus $R = (1/n\pi)(dV/dh)^{1/2}$, and $dV/dh = (dV/dt)(dt/dh)$, where dV/dt is sewage discharge rate and dh/dt is sewage build-up rate in the shaft. The radius of contamination can be estimated in this way by measuring the discharge rate (which should be approximately equal to water consumption) and the rate of buildup in the shaft (Fig. 15, 16, 17).

The melting which takes place in a sewage sink must obviously affect the settlement of overlying strata, and therefore it would be most unwise to locate any structure within a horizontal radius R of a sewer outfall. The maximum observed value of R is 90 ft in several Greenland sewage sinks, but at Camp Century the contamination extended out to a maximum distance of 170 ft (Fig. 18). The separation between structures and sewage sinks should actually be appreciably more than R, since the snow surrounding a sink is warmed and therefore settles more rapidly than snow at the normal ambient temperature for the site. An estimate of the warming caused by a sewage sink can be made by assuming that the sink is a spherical heat source in an infinite homogeneous conducting medium. An appropriate solution of the conduction equation is:

$$\theta_{r,t} = \frac{a}{r} T \operatorname{erfc} \left(\frac{r-a}{2\sqrt{at}} \right) \qquad (2)$$

where $\theta_{r,t}$ is snow temperature at radius r and time t, a is the radius of an equivalent spherical heat source, T is the sewage pool temperature, and a is the thermal diffusivity of the snow. θ and T are measured relative to the undisturbed ambient temperature of the snow, i.e. $\theta_{r,t}$ is temperature disturbance at r and t, and T is the original ambient snow temperature. Calculations suggest that 200 ft can be taken as the minimum safe distance between a sewage outfall and the nearest structure for small sewage sinks.

The other major consideration in siting a sewage sink is the possibility of water supply contamination. Under no circumstances should water wells and sewage sinks be less than 200 ft apart, and much greater separations are desirable, especially for large wells and sinks.

It is widely believed that biological activity in sewage is arrested by dumping into an ice cap sink, since the temperature of the pool is never much above the freezing point. However, sewage sinks do give off strong odors which suggests that there may be some anaerobic activity. This raises another point in respect to hygiene: sinks should be vented to the open air, and precautions should be taken to avoid contamination of living quarters, storage areas and water supplies by malodorous gases. Even when sewer tunnels and outfall shafts are suitably ventilated, there is a possibility of gas diffusion through the pores of the general snow mass.

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*Assur's earlier assumption[3] of paraboloid growth upon a horizontal base of fixed radius now seems unrealistic for long-term growth, although it leads to an estimate of R which differs from the present one only by a factor of $\sqrt{2}$.
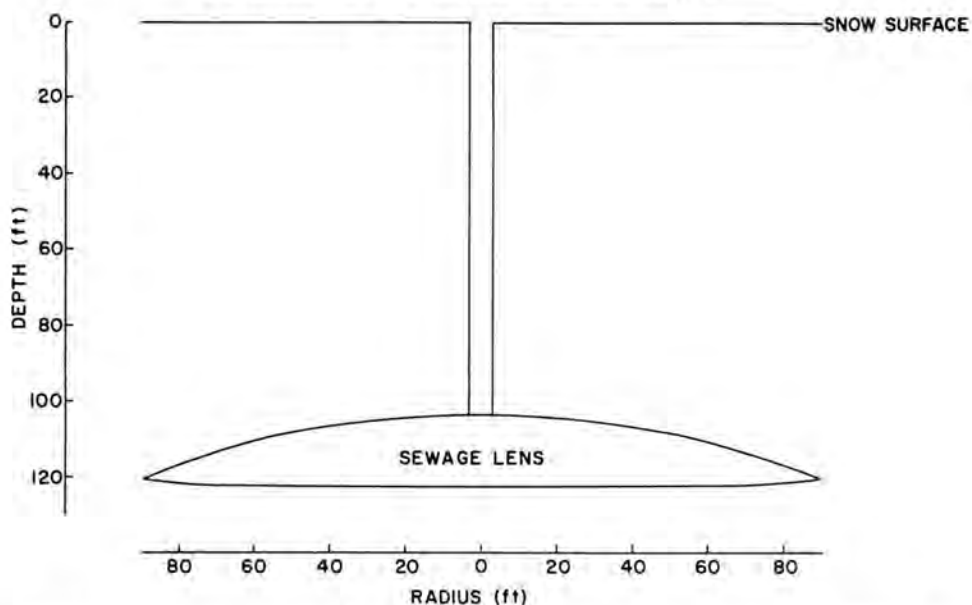
a. *DYE 3 construction camp. Sewage discharge rate was approximately 3000 gal/
    day and vertical buildup rate approximately 36 ft/yr. (Metcalf and Eddy.*[23]*)*
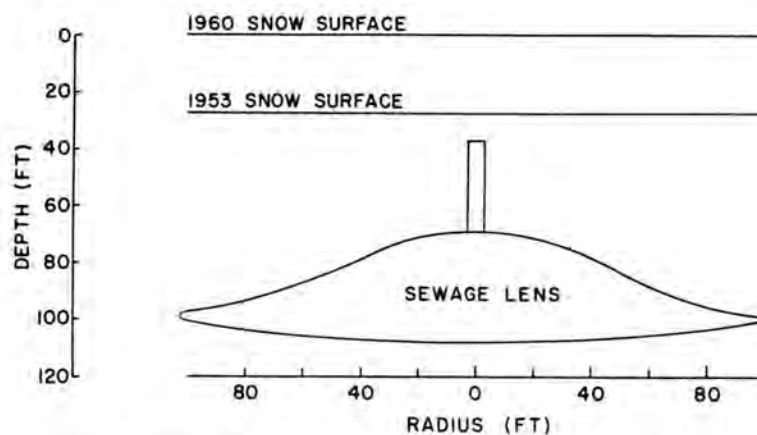
b. *Radar station N-34, Greenland. Sewage discharge rate was
    1000 to 1500 gal/day and vertical buildup rate was about 10 ft/yr.
    (Metcalf and Eddy.*[23]*)*

Figure 15. Cross sections of lenses formed by ice cap sewage sinks.
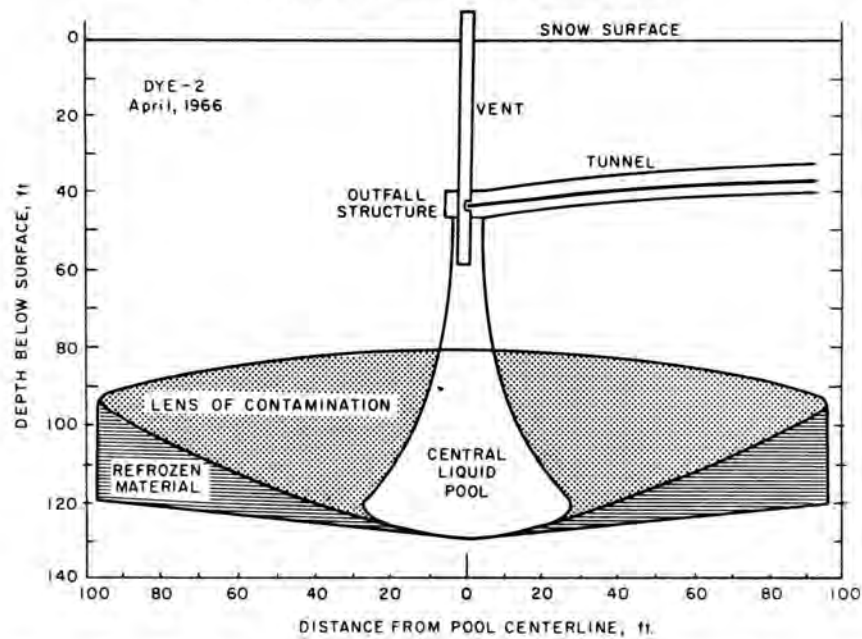
Figure 16. DYE 2 sewage pool and lens geometry. (Reed and Tobiasson.[29])
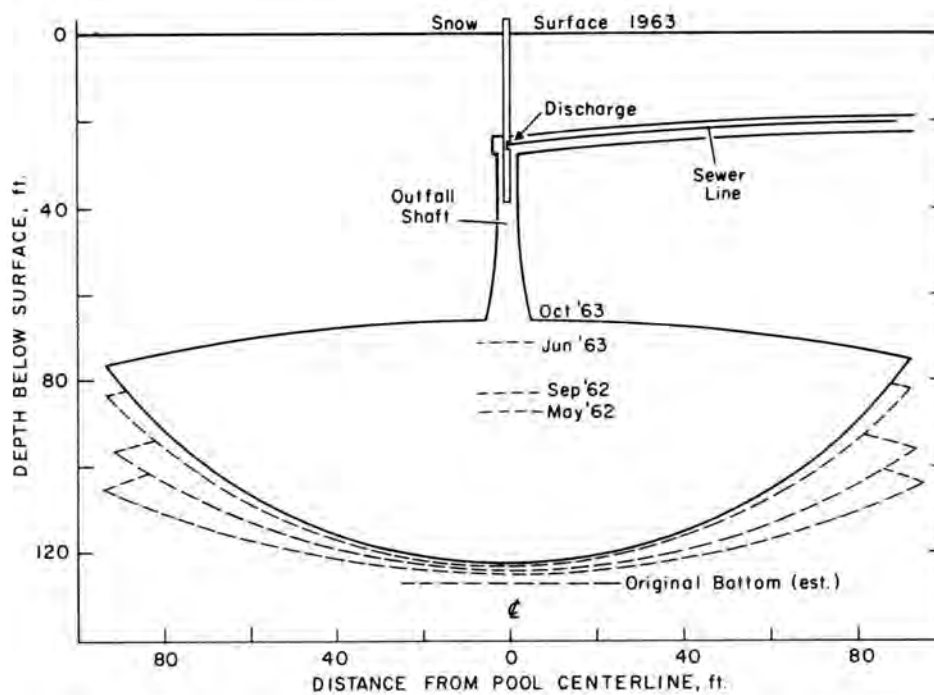
Figure 17. Development of sewage sink at DYE 3, Greenland. (Reed.[28])
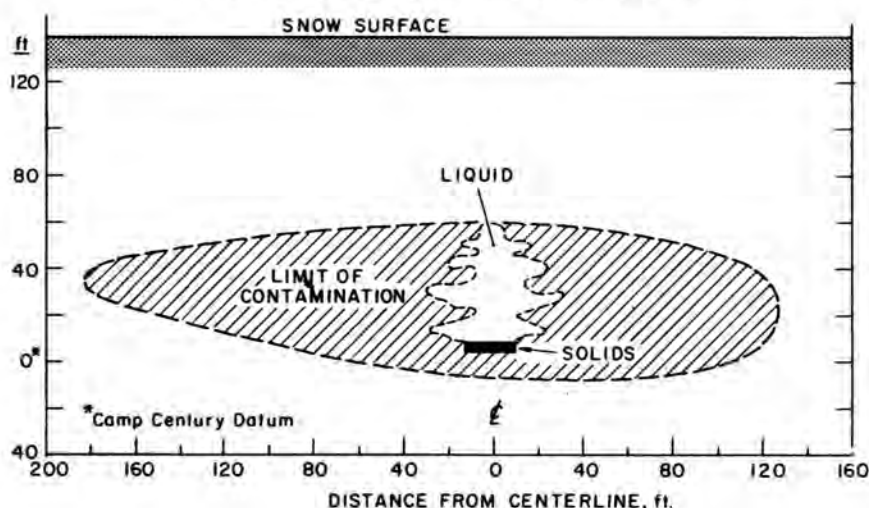
Figure 18. Limits of contaminated snow in the Camp Century sewage sink. The sewage was poured in at a rate of about 1.6 million gal/yr, and the discharge temperature was between 60 and 88F. (Clark.[10])

The main sewer line to an outfall can be an uninsulated nonmetallic pipe (wood stave or plastic), provided the sewage is discharged through it in periodic "slugs" propelled by gravity or pneumatic pressure. Accelerated snow settlement in the immediate vicinity of the outfall causes the sewer line to sag at the outfall end, and longitudinal strain is thus induced in the pipeline. Unless some provision is made for strain relief, say by special sleeve joints with flexible caulking, there is a definite danger that the pipe will pull apart and allow sewage to spill into the snow. To provide additional safeguards against spillage in the vicinity of structures, the sewer line can be carried inside a leakproof tunnel or culvert (Fig. 19).

Latrines

The latrines at camps on polar snowfields are of four main types: pit, bucket, incinerator, and flush.

A pit latrine consists of a deep pit in the snow topped by a box with seats and lids, and protected by a building. A vent pipe (of generous diameter to minimize "frost-up") is run from the pit to the open air, and the latrine building is independently ventilated. Both liquid and solid matter is accepted by the pit. Where low temperatures prevail for the whole year this system is satisfactory, though undesirable at permanent installations. With low ambient temperatures columnar development occurs in the pit, and gentle blasting may be required to topple the "tree" periodically. The method has been employed at U.S. IGY stations in Antarctica.

In bucket latrines, wastes are collected in removable containers (often 55-gal fuel drums cut down or recessed to a suitable depth) placed beneath the fixed seats (Fig. 20). The containers, or "honeybuckets," are hauled away to a downwind dumping area periodically, and there they are either abandoned or fire-cleansed after emptying. The dumped waste may be burned or left to freeze. Bucket latrines in heated shelters are unhygienic and distasteful; used without disinfectant they are disgusting. They are suitable only for temporary, or very small, bases. Toilets on tractor trains provide disposable bags of polyethylene or waxed paper, which are supposed to be buried on a specified side of the trail (the other side providing water supply).

Figure 19. Original main sewer at DYE 3, Greenland. For the first 100 ft outside the station the wood stave pipe was carried inside a corrugated steel culvert (left), which was capable of containing the sewage in the event of rupture in the sewer. The sewer ran another 400 ft through a trench roofed with timber (right). The sewer was laid on a 2% grade, and was supported on transverse sills.

Figure 20. Dimensions for the classic bucket latrine.

*Figure 21. Simple incinerator latrine. The normal seat
is replaced periodically by a burning lid, and the wastes
are then burned. Wastes are consumed completely.*

The simplest type of incinerator toilet is a modification of the bucket latrine in which the
wastes are burned without removing the container. An improvised type might consist of 55-gal
drums bedded in noncombustible material, and having exhaust stacks passing from drums to the
open air.[30] The wastes are burnt periodically by substituting a draught-inducing "burning lid" for
the seat, and firing with a few sticks of kindling and a quart or so of diesel fuel (Fig. 21). (With
this method, it is preferable that only fecal matter should be collected in the drums, a separate
urinal being provided. More elaborate dry-flush incinerator toilets have been produced for use at
semipermanent installations.[41] In these, wastes are passed from the toilet to the attached inciner-
ator by means of a manually operated conveyor. In the incinerator chamber gasoline or oil flames
are directed at the waste by a blower-type heater, and gases are passed off through an exhaust
stack. These devices have not been widely used. The fumes from incinerator toilets are said to
be inoffensive, but they are definitely not alluring.

Flush toilets have been installed at a number of ice cap bases where the provision of heated
sewers has been feasible. One obvious disadvantage of a standard flush toilet is the extravagant
water demand; this problem can be minimized in several ways. Special toilets which use smaller
quantities of water than standard domestic models can be fitted. One well-known type is the
marine toilet, which is pumped out manually and flushed by a hand-controlled valve. There are
also special toilets which flush with a small quantity of water; an extreme example is the Canadian-
manufactured "arctic one-piece plumbing unit," in which the toilet flushes with only one quart of
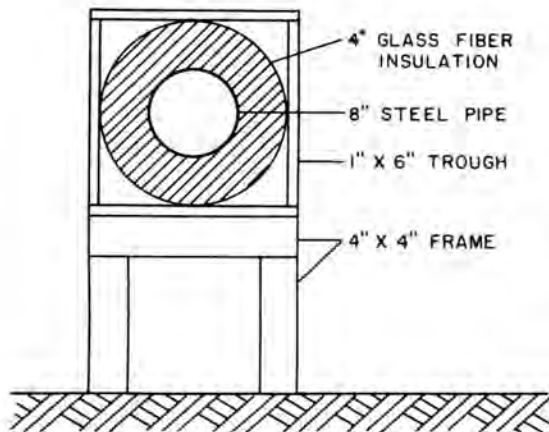
Figure 22. *Section of insulated sewer line mounted in utilidor.*

water.[1] Waste water from showers and hand basins can be recovered for reuse in toilets by passing it through a grease trap and pumping back to a header tank. At some camps, for example, nuclear-powered installations, water supply is no problem and standard units can be fitted. Grinder toilets have been suggested,[11] and hydropneumatic flushing has been tested. One horrible machine was designed to flush with fuel oil, grind the wastes, and feed the whole mess to an oil heating furnace.

Chemical-flush toilets offer a possible solution, but as far as is known they have not been used at ice cap sites on a routine basis. One variety of chemical-flush toilet is the fluid-flush type similar to those used in aircraft. Another is the dry-flush type in which solid wastes are cranked into a disinfectant-filled holding tank by a belt conveyor, which then passes through cleaning rollers.

It is believed that several approaches to sanitation with minimum water use have been explored in detail in connection with civil defense studies of fallout shelters. These ought to be applicable to polar situations.

Sewer lines from flush toilets are normally insulated and heated to permit continuous flow (Fig. 22). The length of heated sewer line can be reduced by passing wastes into a heated collection tank close to the latrines. This collection tank can then be discharged periodically in "slugs" through an unheated outfall line, such as wood stave or plastic pipe. Discharge can be by gravity or air pressure.

Garbage

Organic kitchen wastes can be comminuted in a garbage disposal unit and passed into the sewer system. However, at polar camps it is more usual to collect both organic and inorganic waste in containers and remove the containers to a dumping area periodically. There is usually no point in separating organic and inorganic kitchen refuse, but it is interesting to note that the Russians at Mirny, in Antarctica, have used waste food slops to feed pigs, which were kept in a heated building.

Trash and scrap

The disposal of trash and scrap offers no technical problems, but it should not be relegated to a position of low priority, since partly snow-covered scraps of lumber, wire, and metal littered around a camp can be a considerable nuisance. Combustible trash is usually burned downwind of the camp, but scrap lumber should not be burned without considering its possible reuse. Piles of trash and scrap can generate large snowdrifts so they should be kept well clear of structures, aircraft runways, etc.

Radioactive waste

So far only one station on a polar ice cap has been equipped with a nuclear power plant, but others have been proposed and it seems to be only a matter of time before nuclear energy replaces fossil fuels at remote installations.

All the solid waste produced in the nuclear reactor at Camp Century, Greenland, was packed in concrete casks and removed from Greenland for disposal by land burial or ocean dumping under the direction of the U.S. Atomic Energy Commission.[10] A Danish-American agreement permitted discharge of low activity liquid wastes, such as moderator and coolant water, into the ice cap. The agreement authorized a maximum discharge of 50 millicuries/year in this form, and the actual discharge rate was less than 25% of the permissible maximum. In 1962, 47,000 gal of liquid waste was discharged, and the specific activity was in the range 10^{-9} to 10^{-7} millicuries/cm^3. The sink for radioactive liquids was more than 600 ft from the water wells and the main living/working complex of the station.

It has been proposed that highly radioactive products from nuclear plants in various parts of the world might be disposed of by storage in the Greenland and Antarctic ice sheets.[27] So far, no steps have been taken to implement these suggestions.

Examples of sanitation at polar bases

USAF ice cap radar station N-34, Greenland.[43] The latrine building at the station contained a urinal and four marine water closets (Wilcox, Crittenden & Co. "Skipper No. 6") which were supplied with water from a high tank. Wastes from this building and from the mess hall passed into $4 \times 4 \times 3$-ft-high steel sump tanks, each of which had two 50 gal/min vertical centrifugal sewage pumps. Waste water from the mess hall passed through fixed sink strainers and a grease trap. Sewage was taken from the sump tanks in 3-in. pipes, which joined in the fuel corridor to discharge through a 6-in. wood stave pipe. The wood stave pipe carried the sewage 100 ft away from the building and spilled it into a melted sewage sink. The upper part of the sewage hole was lined with old oil drums welded end to end after removal of their heads. A 5-ft-diam steel riser with inside ladder gave access to the shaft for inspection, and sewage gases were vented through a 2-in. gooseneck pipe. The sewer pipes were wrapped with 0.5 ohm/ft heating wire thermostatically controlled to maintain a temperature of 40F at the pipe wall. Insulation consisted of 4 in. of hair felt.

The design of this station was a pioneer effort, and largely experimental. The fuel corridor suffered differential settlement and became badly distorted when the sewer line to the outfall ruptured and caused melting under the structure. This rupture probably resulted from strain induced by rapid settlement of the sewer near the outfall.

Camp Fistclench, Greenland.[44] Originally at this experimental camp, toilets were flushed with waste water from showers and hand basins, and sewage was passed along 8-in.-diam steel pipe wrapped with 4 in. of glass fiber insulation. The pipes were protected by a timber utilidor, which was elevated above the snow surface on 4×4-in. timber piles. A ¾-in. hot water line was included in the system for additional flushing in case of necessity. Final discharge was to a sewage sink. Later, hot fresh water was used for flushing toilets. Urinals placed at intervals through the under-snow camp consisted of fuel drums half-buried in the snow trench floors, their lower ends being removed to permit seepage into the snow; the small quantities of wash water from the Jamesway sleeping huts were disposed of by tossing outside the door. These Elizabethan practices are not normally endorsed by sanitary engineers.

Camp Century, Greenland.[10] Camp Century had an ample water supply, and standard flush toilets were installed. Large quantities of waste water also came from the generous shower and laundry facilities. The main sewage discharges came from the two latrine buildings, the laundry, the mess hall and the dispensary. The pipes converged on a central sewage collecting tank, which discharged to an outfall in the disposal trench. The sink was situated only 150 ft from the nearest building, and it caused accelerated settlement which distorted the snow tunnels and necessitated the removal of

two buildings. The sink originally was not vented, and it created intolerable odors in nearby living areas. Subsequent venting reduced the stench but did not eliminate it.

USAF radar stations DYE 2 and DYE 3, Greenland. These stations are completely contained within the heated shell of the composite building.and conventional plumbing is fitted. Sewage is collected in a sump tank located inside the composite building, and is discharged periodically in "slugs" to a sewage sink in the snow. Sewage is carried from the building to the outfall in an 8-in. wood stave pipe. This pipe runs beneath the snow surface to a sewage sink 500 ft away from the foundations of the main building. The wood stave pipe is uninsulated and unheated, the sudden discharges of warm sewage being relied upon to inhibit freeze-up. Originally, the main sewer was carried on transverse sills, inside a corrugated steel culvert for the first 100 ft and in a snow trench roofed with timber for the remaining 400 ft. Later, the steel culvert was extended for the full 500 ft, although this seems an unnecessarily expensive procedure.

The sewage disposal systems for DYE 2 and DYE 3 have been studied in detail by Reed,[26] who has proposed various schemes for replacing the existing sinks as they reach capacity.

Little America V IGY Station, Antarctica (and similar IGY stations). Wastes from the two latrine buildings at Little America were discharged into pits directly beneath the toilets. The pits were originally excavated to a depth of 25 ft, but they deepened rapidly with the inflow of warm liquids from showers and wash basins. Waste water was originally collected in heated tanks for periodic discharge into the snow, but it was later decided that these warm holding tanks were unnecessary.

South Pole Station, Antarctica. The present sanitary system has evolved from the original IGY arrangements. Water from the standard 5-gal flush units and urinals in the head discharges together with laundry water into a pit located close to the buildings. Waste water from the galley discharges into a second pit, which again is close to the station buildings. Occasional freezing problems in the second pit are treated by adding 100-lb doses of caustic soda. Seeping sewage has contaminated the snow mine, which was the original source of drinking water and was later used for research purposes. Trash and garbage are burned in an incinerator located in a tunnel under the snow.

New Byrd Station, Antarctica. Standard plumbing is provided in a number of buildings and the sewage is carried in an electrically heated, insulated 4-in. pipe to a heated sump tank. The sewer pipe is insulated with 2 in. of glass fiber and has thermostatically controlled electrical tracing of 7 watts/ft. An outer steel pipe jackets the sewer. Sewage is pumped from the collecting tank to a sink in the snow. Two sinks have been developed, and they are used alternately in order to expedite freezing of the sewage. Trash and garbage are dumped in a special tunnel.

HEATING AND VENTILATING

The principles of heating and ventilating buildings in the ice cap environment are no different from those applied to design for the temperate regions. The major differences in practice are matters of degree and economics.

Heating

Heating load

It might reasonably be assumed that indoor temperatures in polar buildings would be equal to, or less than, the equivalent design temperatures for comparable buildings in temperate regions, since the occupants customarily wear heavy clothing indoors. In fact, it is found that when the occupants of polar buildings have direct access to heating controls they often maintain "breathing level" temperatures which are appreciably higher than the 70 to 75F which might be expected. This may be due to low relative humidity, to thermal stratification, or to the fact that the men are compensating for the deep chilling which occurs during outside work.

Mean annual air temperatures on the ice sheets of Greenland and Antarctica are mostly in the range from +10 to -70F. If buildings are constructed under the surface of the ice sheet, and if they are prevented from warming their surroundings, then they may experience an outside temperature close to the mean annual air temperature during the entire year. However, subsurface buildings are not exposed to any significant winds.

Free air temperatures above the snow surface vary considerably, from values near the melting point in summer down to -125F at the coldest sites during winter. Solar radiation on a horizontal surface varies from about 1000 langleys*/day in midsummer to zero in midwinter. Surface winds tend to be strong and persistent; mean annual wind speeds are commonly in the range 10 to 20 mph. Generally speaking, only very light winds would be expected when the temperature is extremely low; when strong blizzard winds blow there is usually an appreciable rise in temperature. The most severe cooling conditions might arise with a combination of moderately low temperatures and brisk winds, e.g. -40F and 20 mph. Detailed climatic data are given elsewhere in this series (CRSE Monograph I-A3). From these data, and from known temperature lapse rates for altitude and latitude, it is possible to prepare heating degree-day summaries for any site.

Heat losses and insulation

Heat loss by conduction is usually limited by the use of rigid cellular plastic insulation or paper honeycomb with filling. In light buildings the insulation is usually an integral part of the structure, being bonded between metal sheets as a load-bearing core. Experimental buildings have also been made with insulating plastics foamed in place, the object being to reduce bulk for shipment of materials to the site. The heat transfer coefficient U for insulated building panels used at ice cap sites is commonly about 0.1 Btu/ft^2 hr °F for moderate outside winds.

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*Cal/cm^2

Actual heat losses from a complete building consist mainly of conduction losses and convection losses through doors, ventilators, cracks, etc. With all cracks properly sealed and vestibules on main entrances, a realistic goal for the overall U factor is 0.2 Btu/ft² hr °F or lower. Relatively low ceilings and extra insulation in ceilings can lead to significant savings in heat.

Longwave radiation losses can be cut down by sheathing the building with polished metal sheet, but it is questionable whether this is worthwhile in most cases. For buildings above surface it may be preferable to finish the exterior a matt black in order to take advantage of shortwave solar radiation in summertime; the difference in longwave emissivity between black and white finishes is negligible, but the shortwave reflectance can change by a factor of 3 or 4.

Under normal circumstances there is very little chance of condensation on the inside of panels which have a U factor of about 0.1 Btu/ft² hr °F. Since the absolute humidity of cold outside air is low, the relative humidity drops to very low values when it is drawn into a building and heated. However, if there are any metal objects which penetrate the insulation, frost or condensation will form around them inside the building. For this reason metal connections through building skins are avoided. Water vapor may be introduced into buildings by artificial humidification or by cooking, laundry, bathing, etc. and vapor barriers ought to be provided. With typical insulated sandwich panels the impermeable sheathing provides a vapor barrier when all joints are adequately sealed.

When windows are fitted to polar buildings, double glazing is essential.

Because heating fuels are so expensive to deliver to remote sites, it may be justifiable to use thicker insulation than that which would normally be regarded as the economical thickness for design in temperate regions. Once the working life of a building has been stipulated, the cost of additional insulation can be balanced against the fuel saving over the life of the structure.

Energy sources for heating

At ice cap sites, the only natural sources of energy for heating purposes are solar radiation, wind, and temperature differences within the snow and between snow and air. Solar radiation can provide a useful supplement during summer, but none is available during winter; apart from simple expedients like painting surface structures black, measures for utilizing solar energy (e.g. parabolic reflectors, solar cells) are likely to be too troublesome for practical use at the present time. Wind generators could certainly be used, but they are both feeble and erratic in output; a reasonably large unit could only be expected to provide a few kilowatts with fairly strong winds blowing. Heat pumps are probably too inefficient to be considered for use at remote polar sites.

In principle, nuclear fuels appear to be the most desirable source of energy for remote sites. The feasibility of powering a large station with a nuclear reactor was demonstrated at Camp Century, Greenland[10] but there is still little evidence that a nuclear plant can be justified economically. At present, the installation of plants in the megawatt range seems to be feasible, but plants suitable for meeting smaller power demands have not yet been justified.

The basic heating requirements of all the stations which have been built on permanent snow-fields have been met with fossil fuels. Coal was used at a few of the early stations built close to the sea, but it cannot be regarded seriously as a fuel for polar stations (unless a local deposit can be exploited). Liquefied gases could be used, but as far as is known they have not been used at fixed bases on a large scale. The standard source of heat is fuel oil of one kind or another. If fuel oil has to be transported by air during some stage of its delivery to a base it becomes very costly.

Because fuel is so expensive when delivered to a remote station, every effort should be made to exploit it to the full. This means that no heat whatsoever should be allowed to go to waste without some attention being paid to the possibilities for reclamation. Something like two-thirds of the heat supplied to diesel-electric generators by the fuel is potentially available for reclamation by means of heat exchangers on the coolant and exhaust systems and by engine room venting; this heat can be utilized for space heating, water heating or snow melting. Oil burning heaters should be arranged so as to yield the maximum amount of useful heat before exhausting. Electrical equipment, such as light bulbs, electronic devices, motors, and domestic appliances, is capable of supplementing the space-heating system. Warm air exhausted from heated buildings can be used to temper incoming air.

In undersnow facilities there is a further reason for cutting heat losses to an absolute minimum; heat loss warms the surrounding snow and accelerates deformation rates.

Heating systems

The basic requirements for a heating system at a remote base are efficiency and simplicity. The choice of system will be determined partly by the size and permanence of the station, the relative locations of buildings and the facilities and functions of the base.

Independent oil-fired heaters provide the most direct approach to space heating. They range from small portable burners to moderately high capacity oil furnaces. As far as is known, very large furnaces have not been used at ice cap stations because of the problems involved in distributing steam or hot water from a central heating plant to dispersed buildings. In small temporary buildings, open-flame kerosene heaters have been used, although they are highly unsuitable in view of the hazards of cold fuel and combustion products. In simple shelters it is better to use pot-type vaporizing burners with direct exhaust out of the building. With only free convection and radiation to distribute the heat there is little uniformity of temperature, so that some form of heat distribution is desirable, even if it consists only of a fan and flexible trunking. Perhaps an optimum type of heater for a small building would be similar to those used in house trailers, which have a simple pot burner and hot air circulation through ducts and registers. Larger buildings at semipermanent stations can be heated with standard domestic or commercial pressure-atomizing oil furnaces. Hot air circulation through ducts and registers is often preferred for its simplicity, but ducts are bulky and the system can become unbalanced where occupants have access to registers. Forced hot water circulation is very satisfactory, but provision must be made for easy drainage of the system in the event of shutdown. It has been suggested that heating panels in walls or ceiling are preferable to baseboard heaters. Oil-fired steam heating is efficient, but since it calls for skilled operation and maintenance it is best adapted to large plants. Oil heaters should have an efficiency greater than 70%.

In very cold environments, diesel fuel and other fuel oils require preheating to reduce their viscosities. It is customary to maintain a small supply of fuel in a heated tank.

Electrical heating is clean, safe and efficient, and it permits distribution from a central plant to widely dispersed buildings without much energy loss. Radiators, convectors, combination radiator/convectors, panels and heating elements set into the floor have all been used with success. There is some conflict of opinion concerning the most effective devices for producing uniformity of temperature. Both convectors and underfloor heating are reasonably effective in minimizing thermal stratification; preferences for or against radiators may be to some extent subjective, perhaps influenced by the type of clothing worn by building occupants. When a high rate of heat input is required it may be necessary to supplement underfloor heating to avoid unduly high floor temperatures. Radiators with exposed elements should be shielded to eliminate fire hazard.

Reclaimed heat from diesel generators, flue gases, electrical equipment and ventilation systems can be transferred to air or liquid for space-heating purposes. Heat recovery from high temperature sources, such as engine exhaust and coolant, is effected by means of conventional heat exchangers. With low temperature sources, such as the air surrounding electronic equipment or mechanical plants, the warmed air may be circulated directly or a special plenum chamber for heat exchange may be installed. Low temperature exhausts, including outgoing stale air from heated buildings, may be passed through a coaxial line to temper very cold incoming air.

Ventilation

Good, positive ventilation is of great importance at ice cap installations. The ventilation system must not only provide fresh air for respiration and combustion, it must also provide heat control to avoid the development of "hot spots" in load-bearing snow or ice.

There have been a number of instances of death or serious incapacitation from anoxia or from carbon monoxide poisoning at polar camps. There have undoubtedly been many more cases in which occupants of polar buildings were mildly debilitated, perhaps over long periods, by inadequate oxygen supply or carbon monoxide. Many ice cap stations are at high elevations – 5000 to 10,000 ft above sea level – and the problem tends to be more severe than would be the case at sea level.

Some modern undersnow facilities have suffered undue deformation and damage as a result of improper or inadequate ventilation. In many situations it is necessary to maintain a circulation of cold air to avoid heat transfer to snow foundations and load bearing snow in tunnel walls and roofs. If this circulation is not provided, the potential working life of the facility can easily be reduced by a factor of 3 or more. In some cases, gross mismanagement of ventilation systems has resulted in warm air being exhausted directly against load-bearing snow.

Air demands

The minimum exchange rate of air for oxygen replenishment and maintenance of carbon dioxide at a safe level is about 4 ft³/min for each occupant of the building. In conventional buildings this demand can usually be met by infiltration through cracks and openings, but in polar buildings, where thorough sealing is required for thermal efficiency, infiltration should be discounted for ventilation purposes. Actually, ventilation ought to provide for removal of odors and irritants, so that much more than 4 ft³/min is required.

Figure 23 gives standard curves showing the minimum ventilation rates for respiration and removal of body odors as functions of available living space. The odor removal curves are based on laboratory results for adults of average socio-economic status, but in view of the generally low standards of personal hygiene which prevail at many polar bases it might be advisable to accept the higher ventilation rates found necessary in tests with laborers and persons of lower socio-economic status.[2] A 50% increase to take care of this factor is suggested.

Cigarette smoking is a common source of irritation, and must be considered in ventilation design. In one test,[24] subjective judgment by nonsmokers indicated that a ventilation rate of 25 ft³/min per smoker maintained an acceptable air quality, and ventilation rates less than 14 ft³/min per smoker caused definite irritation. All subjects were depressed when the air flow was less than 15 ft³/min per smoker.

There are other local sources of odor, such as foodstuffs, cooking fumes, sanitary facilities and workshop or laboratory processes. These usually require separate ventilation arrangements for direct exhaust or adsorption filtering.
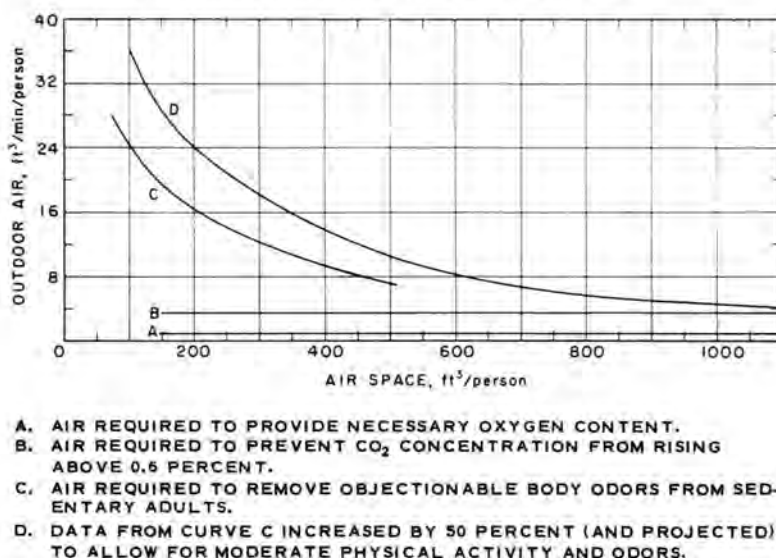
A. AIR REQUIRED TO PROVIDE NECESSARY OXYGEN CONTENT.
B. AIR REQUIRED TO PREVENT CO_2 CONCENTRATION FROM RISING
   ABOVE 0.6 PERCENT.
C. AIR REQUIRED TO REMOVE OBJECTIONABLE BODY ODORS FROM SED-
   ENTARY ADULTS.
D. DATA FROM CURVE C INCREASED BY 50 PERCENT (AND PROJECTED)
   TO ALLOW FOR MODERATE PHYSICAL ACTIVITY AND ODORS.

*Figure 23. Minimum ventilation requirements to avoid air vitiation
and obnoxious body and smoking odors. (Arctic Units Ltd.)*

Air exchange requirements, and hence heating demands, can be cut down by recirculating air after it has been passed through adsorbent filters and by using antiseptic or disinfectant deodorants. In a typical polar camp a few pounds of activated coconut shell per person per year should suffice for odor adsorption.

Air intakes and exhausts

Special problems in the design of air intakes and outlets arise as a result of low temperatures, high winds and prevalence of blowing snow.

Air intakes must be arranged so as to avoid ingestion of windblown snow, which may block the intake or accumulate inside the building. This is no problem in undersnow installations, but it must be considered carefully in above-surface structures. Intakes have been fitted in floor and wall boxes, and also in stacks which rise above the lowest layers of blowing snow, where particle concentrations are greatest. Whatever arrangement is adopted, it should have an element of redundancy to insure against air starvation in the event of partial blockage. The actual entry point of an intake should be at outside air temperature to minimize snow adhesion and icing. It may be possible to lead incoming air through a duct arranged coaxially with the exhaust air duct and so recover some of the heat lost through the exhaust.

As far as possible, stale air and combustion products should be carried directly to the outside air. This is especially important in undersnow facilities, where expelled air can be unhealthy and structurally damaging if recirculated through the ventilation system. Exhausts protruding into the wind and blowing snow may be susceptible to back-draughts and blockage, but with care trouble can be avoided. The outlet end of the exhaust should be well above the snow surface to minimize snowdrifting and snow adhesion, and it should be cold (or insulated) to avoid icing.

In some cases adequate air circulation can be maintained by natural draught and regulated by dampers. When undersnow buildings exhaust directly to the surface, chimney heights can easily reach 20 to 40 ft. In other cases circulation is maintained by fans.

It is important to ensure that clean fresh air is drawn into ventilation systems. This may seem an unnecessary consideration at remote polar sites, but it is a fact that foul air has been used for ventilation at more than one modern subsurface ice cap station. In one case malodorous air from the vicinity of a sewage sink was used to ventilate living quarters, and in another case air heavily polluted with diesel fumes in a vehicle tunnel was drawn into living areas. Above-surface stacks should be separated as far as possible, with intakes upwind of exhaust.

Ventilation of undersnow tunnels

With undersnow tunnels and other cavities special ventilation considerations apply. In order to minimize deformation rates in tunnels, foundations, etc., temperatures must be kept as low as possible. In winter it is relatively easy to circulate cold air from the surface and thus remove any stray heat introduced by equipment and activity. In summer, however, surface air is warmer than the undisturbed subsurface snow; it then becomes necessary to exclude surface air from the tunnels and to find another source of cold air for removal of stray heat.

Below a depth of 30 ft or so, snow remains at a constant temperature throughout the year, and that temperature is equal to the mean annual surface air temperature. The snow is also permeable, so that it provides a reservoir of cold air which can be drawn upon in summertime. The only problem is to devise a practical way of tapping this air reservoir.

It was suggested originally that cold air should be drawn from the strata underlying tunnels through cased boreholes.[46] Boreholes of about 14-in. diameter were driven to a depth of about 40 ft below tunnel floors, and were cased in the upper portions. Fans were mounted at the heads of these "air wells," and air was pumped from the bore to the tunnel. It was necessary to run the wells continuously throughout the year to avoid any possibility of progressive warming in the air reservoir. In practice, air wells proved to be somewhat unsatisfactory for the production of large flow volumes. They also tended to "short circuit" by drawing air directly down the outside of the casing.

The chief shortcoming of the air well is that it imposes steep pressure gradients and high seepage velocities in the relatively small mass of snow immediately surrounding the bore, and therefore it makes high pumping demands. For practical purposes it seems preferable to draw air from large plenum chambers, such as unheated storage tunnels, which can be replenished from the surrounding snow by very slow seepage.[22] In tunnels which are partly lined, like the Wonder Arch trenches which have a steel roof arch and snow walls, air can be drawn directly through the lower walls simply by putting the whole tunnel under a slight negative pressure with exhaust fans or stacks.

At Camp Century the air blast coolers of the nuclear reactor stimulated vigorous seepage of air through the wall of the tunnel housing the fans. Unusually rapid air flow along preferred seepage paths in the most permeable snow layers caused snow evaporation and left the wall surface honeycombed with holes.[22] If allowed to develop too far, this kind of effect might compromise the structural integrity of load-bearing snow. A converse effect can be envisaged, in which air is drawn towards a surface colder than the source area of the air. Condensation and progressive blockage of the snow pores might then occur.

Carbon monoxide

Carbon monoxide poisoning has always been a danger in the polar environment, where fuels are often burned in confined spaces. Dangerous concentrations can occur in tents, houses, tunnels and vehicle cabins. In large undersnow installations internal combustion engines, from the small

chain saw variety to large tractor diesels, are often operated without direct ventilation to the out-side air, and open-flame equipment is occasionally employed.

The basic precaution against a dangerous concentration of carbon monoxide is positive ventilation. This is particularly important where internal combustion engines and open flame stoves are operated inside tunnels and shelters. Air contaminated by exhaust gases should be conducted to the outside air directly, without leaving any possibility for the contaminated air to be drawn into the ventilation of other occupied areas. The importance of this obvious point cannot be overstressed; in the past, vehicles have frequently been run for long periods inside portals which act as the main air intake for tunnel systems.

Carbon monoxide warning systems should be installed (and maintained) in all subsurface com-plexes and tightly sealed buildings. In a sophisticated station the carbon monoxide detectors can be made to actuate warning lights and horns when certain concentrations are reached and, if neces-sary, they can also be arranged to operate emergency switching for shutdown of engines and furnaces and for emergency ventilation. Even in simple shelters and vehicle cabins it is worth installing detectors of the color-change type.

While the critical concentration for alarm actuation is to some extent arbitrary, the recommended threshold limit for 8-hour exposure 5 to 6 days per week is given by the American Conference of Governmental Industrial Hygienists (1963) as 100 parts per million. Alarms are often set to respond to concentrations two or three times higher than this limit.

Fire Protection

Fire in the polar regions is a fairly common occurrence. The consequences of a damaging fire can be very serious at remote sites, which may be completely isolated from the outside world for long periods. Major factors in the planning of fire protection at ice cap sites are the lack of water and the prevailing low temperatures. Unless a station has a water well or large water storage capacity it will be unable to provide conventional fire-fighting facilities, and if there is no piped water distribution, sprinkler systems cannot be fitted very readily. Extinguishers which are liable to freeze cannot be stored in unheated buildings, tunnels, or vehicles.

Ideally, fireproof construction ought to be standard for polar construction, but for a variety of reasons it is rarely feasible to achieve this ideal. The alternative is to provide heat shields and incombustible materials in critical zones, and fire resistant materials for sheathing structures. Intumescent paint is sometimes a useful safeguard. High standards should be demanded for elec-trical wiring.

Dispersal of buildings is effective in limiting the spread of fires, but dispersal is architecturally inefficient. It ought to be possible to provide adequate damage control in compact structural group-ings with fire walls, although a separate survival building equipped with all the basic necessities of life and with radio should always be set up at some distance from the main complex.

Provision and maintenance of emergency exits is of prime importance. There should be ample exits, and precautions should be taken to avoid any possibility of ice or windblown snow jamming or blocking exits.

Temperature, temperature-rise, and smoke alarms can be installed in polar camps, and if the station has adequate water supply and distribution, automatic sprinklers can be fitted in heated buildings. All the nonfreezing standard extinguishers (carbon dioxide, dry chemical) can be installed and used satisfactorily.

Special attention should be paid to fire control during the design of ventilation systems. It should be possible to reduce or cut off the air supply to selected areas, and to ensure that smoke from a limited fire does not invade the entire ventilation system. There is a particular need for breathing apparatus for fire-fighting in subsurface installations.

Stations should be patrolled periodically by a watchman. There should be a trained safety officer who checks fire hazards and maintains fire-fighting safeguards (condition of alarms and extinguishers, fire drills). All personnel manning remote stations should receive some instruction in fire protection.

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13. ABSTRACT

The topics covered in the monograph include water supply, waste disposal, heating, ventilating and fire protection at installations built on polar ice sheets. The section on water supply discusses energy requirements, consumption rates, water quality and treatment, techniques and equipment for melting snow and ice, and water distribution systems. A number of actual water supply systems are described in detail. The section on waste disposal deals with sewage and sewage sinks, latrines, garbage, trash and scrap and radioactive waste. Examples of sanitation systems at polar bases are described in some detail. The section on heating discusses heating load, heat losses and insulation, energy sources, and heating systems. The ventilation section covers air demands, intakes and exhausts, ventilation of undersnow tunnels, and carbon monoxide problems. The report concludes with some notes on fire protection.

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Antarctica -- Construction	Sewers
Cold weather construction	Snowfields
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