SOME STRUCTURAL AND THERMAL CHARACTERISTICS OF SNOW SHELTERS

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Introduction

THE current rapid expansion of long-range aircraft operations, both military and civilian, into arctic regions suggests the need for critical appraisal of techniques and equipment required for survival problems and emergency shelter construction in extreme cold. The need for practical, easily built shelters is apparent in many arctic activities, such as mid-winter travel and military manoeuvres. The use of naturally occurring compacted snow as a structural material for dwellings has a long history, principally among the Eskimo of the Central Canadian Arctic. Stefansson (1944) and others (Mathiassen 1928, Birket-Smith 1929, Rowley 1938, and Browne 1946) have described Eskimo tools and methods for the construction of the familiar, domed snow-block house. Relatively little is known, however, concerning the thermal and structural properties of snow shelters.

Some temperature measurements taken at various levels inside a snow house during occupation have been recorded (Stefansson 1944, Mathiassen 1928). Koppes (1948) discussed some theoretical aspects of the thermal characteristics of the snow house and, making several assumptions, estimated the heat required to maintain a temperature difference of 50°F between inside and outside air. He calculated that the metabolic heat of four occupants was enough to sustain such a temperature difference in a house with the following characteristics: domed snow-block construction with door and entrance trench built on a lower level than the shelter floor, forming a "cold trap", interior volume 410 cubic feet, floor diameter 11 feet, average wall thickness 9 inches, thermal conductivity for compact snow 1.48 BTU/in./ft.^{2}/hr./°F (Handbook 1950), outside air movement 25 miles per hour, and one air change per hour by diffusion through the open door without roof ventilator. This estimate confirms the casual observations of those familiar with such shelters as regards their remarkable ability to protect from wind and low air temperatures. Koppes also reports a suggestion of Sir Hubert Wilkins for the construction of snow houses with unconsolidated snow by using a pneumatic form. This would provide an

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extremely simple technique requiring little experience or skill and would considerably extend the availability of snow as building material.

The possible influence of arctic microclimates on the thermal characteristics of snow houses is suggested by the recent work of Johnson (1954) and Pruitt (1957). These studies indicate the substantial advantage that can be gained by using the existing heat flow from the relatively warm ground outward through the snow cover. Temperature measurements at the subnivean ground surface in the spruce forests of interior Alaska were reported to be in the neighbourhood of +20°F to +25°F These temperatures are remarkably stable even with snow depths as small as 1 foot and with air temperatures at the snow surface as low as —55°F. Subnivean ground temperatures appear to vary considerably with the character of the ground surface, being highest over moss and grass and lowest over gravel, but they are nearly always well above outside air temperatures. Similar, though smaller, thermal gradients exist in the snow cover over arctic tundra (Johnson 1954) and sea ice (Holtsmark 1955). Temperatures at various depths in a permanent antarctic snow-field were measured by Wade (1945). At a depth of 4 metres they were found to remain essentially constant at approximately the same value as the mean annual air temperature. It has been frequently noted in arctic regions that temperatures in valleys or hollows are generally lower than on nearby hills or ridges. The difference may amount to 20° to 30° F in the absence of wind. The disadvantage of building a shelter in a valley bottom or of sleeping in a simple hole in the snow is apparent.

The practical use of these arctic microclimates becomes important when fuel must be conserved or is not available. Success in the use of the ground heat to raise the temperature of a shelter requires that it is well insulated. Snow is an abundant, efficient insulating material. Its use can give a very considerable thermal advantage so that survival will be possible with a minimum of clothing and equipment in the relatively warm interior of an efficiently constructed shelter. The use of an entrance "cold trap" or adequate door of snow-block or other construction is, of course, essential.

Shelter construction using compacted snow

During the winter of 1955-6 the feasibility of snow-shelter construction using loose, unconsolidated snow as building material was studied. Experimental shelters were built near the River Laboratory of the Arctic Aeromedical Laboratory, Ladd Air Force Base, Fairbanks, Alaska. The Fairbanks region has a typical interior Alaska climate with extreme cold and little wind in midwinter. The snow is rarely compacted by wind and is generally unsuitable for cutting snow blocks or digging snow caves. Snow depth during the winter ranges roughly from a few inches to 2 or 3 feet. Average density is of the order of 0.2 gm./cm.^{3}.

Browne (1946) suggested a method for rendering snow of this type fit for cutting blocks by tramping a suitable area with ski or snowshoes and then allowing the area to remain undisturbed for a few hours or over night. However, the compacting and settling process requires several hours and the resulting blocks are frequently very fragile and non-homogeneous. Birket-Smith (1929) mentioned tramping soft snow to compact it. He also described a dome-shaped, temporary Eskimo shelter consisting of bent branches covered with skins and a layer of loose snow thrown over the outside.

Several experimental shelters were built by the method suggested by Wilkins (Koppes, 1948) using a weather balloon inflated to approximately 4 feet in diameter. The construction procedure was as follows:

(a) excavating a hole in the snow to the ground of sufficient size to take the balloon;

(b) shovelling snow from the surrounding area over the balloon to a depth of about 1 foot;

(c) leaving the shelter undisturbed for at least 1 hour;

(d) excavating a hole on one side, deflating the balloon, and further digging out the interior as required;

(e) making a door of snow blocks, garments, or other available material.

The interior of such a shelter can be glazed to increase its strength, if desired, by raising the temperature inside with a suitable stove.

The use of a weather balloon or similar pneumatic form is not indispensable for this type of construction. Similar shelters were built by using a parachute laid over a pile of spruce and willow branches and small trees. Survival kits, aircraft fragments, etc., would serve just as well. Even these are not necessary, only more time and work is required to pile up and excavate a snow mound. No skill or special tools are needed, snowshoes or hands can be used for shovelling. The Nunamiut Eskimo of the Anaktuvuk Pass region of northern Alaska are familiar with this type of construction. Osgood (1936) has described a similar emergency snow shelter used by the Kutchin Indians of northwestern Canada.

The success of this general method depends on a type of artificial compaction known as *depth processing* (Taylor 1953), the existing thermal gradient in the snow cover is disturbed and the snow is thoroughly mixed by being shovelled. Shakhov (1948) discussed the "sublimation-thermodynamic theory" as the most probable way of accounting for consolidation within a snow cover in the absence of wind. The change in hardness is presumed to be dependent on the sublimation of water vapour adjacent to snow crystals of relatively high temperature and its subsequent recrystallization on snow crystals of lower temperature. This [cementing] process, which takes place slowly in a natural snow layer, proceeds very much faster following disturbance and mixing when many "cold" and "warm" snow particles are placed close to each other and the snow of the whole layer is exposed to the relatively low temperature of the air above. This is followed by rapid recrystallizing of water vapour and cementing of the particles. Table 1 illustrates the thermal conductivity of snow as compared with various other insulating materials.

Table 1. Thermal conductivity of snow compared with that of various insulating materials.

	Density *gm./cm.^{3}*	*Porosity* *per cent air*	*Thermal Conductivity* *(cal./cm.^{2}/sec./°C./cm.) $\times 10^{-4}$*
Snow	0.39	57.5	6.4
	0.28	69.5	2.49
	0.14	84.7	1.52
Brick	—	—	15*
Dry soil	—	—	3.3*
Sawdust	—	—	1.2*
Rock wool	—	—	0.94*

The figures for porosity are from Bader *et al.* (1939).

Thermal conductivity values for snow are from Yosida and Iwai, cited by Mantis, (1946).

* Handbook of Chemistry and Physics, 32nd edition, 1950-1.

A detailed record of the changes in density and hardness was obtained during the construction of one such shelter on February 28, 1956. The snow depth was 31 inches. The lowest 6 inches consisted of depth hoar. The average density was 0.22 gm./cm.^{3}. "Hardness" (yielding pressure), measured with a Canadian Snow Test Kit[1] hardness gauge, ranged from 8 gm./cm.^{2} to 80 gm./cm.^{2}. Air temperature at 3 feet above the snow surface was —17°F.

A weather balloon was covered with snow and left undisturbed for 4 hours. The density of the snow in the wall of the completed house was 0.28 gm./cm.^{3}. Hardness varied greatly from place to place, sample figures ranged from 200 gm./cm.^{2} to 850 gm./cm.^{2}, but the rapid changes accompanying the compaction process are indicated by these values. Snow of these physical characteristics is fit for structural purposes. The final thickness of the wall was 14 inches at the top and approximately 3 feet at the base. The interior ceiling height was 4.5 feet. Floor diameter was 6 feet.

Thermistors were installed in this shelter immediately after construction and positioned 4 inches below the ceiling, at the centre of the interior, and 4 inches above the floor. The floor was carefully cleared of snow, exposing the sod of the ground surface. The door was sealed with snow and temperatures were read within 10 minutes, the time then being 1530. Typical temperature measurements taken in the unoccupied shelter and its environs are listed in Table 2. It can be seen that the interior temperatures attained rough equilibrium with the ground surface temperatures during the period of observation. The air temperatures of the interior remained nearly constant for a range of outside air temperatures from —12°F to —40°F. This represents a maximum temperature difference of 60°F. It is clear that a considerable thermal advantage is gained in a well-built snow shelter without artificial heating even during periods of extreme cold when maximum use is being made of ground heat.

During occupancy of a snow shelter of this type for a period of 11 days temperatures were measured at various times, using an alcohol thermometer. They are listed in Table 3, for the contents of which we are indebted

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[1] Committee on Snow and Soil Mechanics, N.R.C., Ottawa, Canada.

to Dr. Horace F. Drury, Arctic Aeromedical Laboratory. The door of this shelter consisted of the canvas pack of a discarded back-type parachute. Temperatures were measured 4 inches above the floor.

Snow-block construction

Some observations were made on domed shelters constructed of snow blocks on the sea ice about 5 miles from shore near Barter Island, Alaska, in April 1956. Two snow-block shelters were constructed, one directly on the sea ice after clearing away 4 inches of snow, and the other on a drift about 18 inches deep. The blocks were cut from an 18-inch drift of snow having a density of 0.39 to 0.46 gm./cm.^{3}, and a hardness of about 80 to 200 gm./cm.^{2}. One inch of depth hoar was found at the bottom of the snowdrift. The best snow for block-cutting had a density of about 0.30 to 0.35 gm./cm.^{3} and a hardness of about 150 to 200 gm./cm.^{2}, but such snow was relatively rare. Both an ordinary carpenter's saw and a standard Air Force survival saw were used with equal ease. Block dimensions were 20 by 12 by 6 inches. Interior dimensions were 7 feet in diameter at the floor by 5 feet high from floor to ceiling. Both shelters were constructed without attempting to include a below-floor-level entrance. Cracks between blocks were plugged with loose snow both inside and out. Doors consisted of snuggly fitting snow blocks.

The prevailing ambient air temperatures were not sufficiently low to provide a rigorous test of the effectiveness of these shelters, but some observations are of interest (Table 4). All temperatures were recorded with shelters unoccupied and doors sealed, except as indicated. Thermistors were mounted 6 inches below the ceiling, 4 inches above floor level and in the centre of the shelter.

The data of Table 4 suggest that the subnivean microclimate on arctic sea ice can be used to provide a relatively warm dwelling. In addition to the conventional domed snow houses a trench was constructed by digging into a drift to a depth of 2.5 feet. Its length was 7 feet and the width 2.5 feet. The roof was made of horizontal snow blocks. With one occupant and a snow-block door the interior temperature at sleeping level, 6 inches above the floor was 20° to 24°F. It was surmised, but not experimentally verified, that the snow trench was a more efficient shelter than the domed houses. It had not such high convective heat losses by wind and was probably better insulated by virtue of its much thicker walls.

Discussion

The observations described show that the main advantage of snow shelters stems from the fact that an insulated air pocket is warmed by heat derived from the heat reservoir of the earth.

In spite of the relatively high inside temperatures of the shelter as compared with those of the outside air the occupants can still loose considerable

Table 2. Temperatures of unoccupied snow shelter and environs (°F.).

Date and time	*Outside air 3 ft. above snow surface*	*Ground surface beneath undisturbed snow, 20 ft. from snow shelter*	*Interior of snow shelter*		
			Top	*Centre*	*Floor*
Feb. 28, 1956 1530	—17	+19	+16	+18	+16
Feb. 29, 1956 0815	—36	+20	+20	+20	+19
March 1, 1956 0800	—40	+19	+18	+18	+19
March 5, 1956 0800	—36	+16	+16	+16	+16
1630	—12	+17	+15	+16	+16

Table 3. Inside and outside air temperatures of snow shelter (°F.). Measurements taken at various times during an 11-day period.

Conditions	*Outside temp.*	*Inside temp.*
No door, unoccupied for several hours	+4	+8
No door, unoccupied for several hours	—2	+7
Canvas door in place during the following measurements:		
Unoccupied	—7	+14
Unoccupied for 2 hours, 1 candle burning	—14	+21
Two occupants, plus a 2nd candle, for ½ hour	—14	+24
Two occupants overnight	—2	+21
One occupant	—49.5	+20
Unoccupied for several hours	—28	+14
Two occupants, 2 candles, for 15 minutes	—48	+23.5
Two occupants overnight	—55	+19
Unoccupied	—38	+14
Unoccupied, 1 candle	—42	+18
Morning, 2 occupants overnight	—10	+19
Unoccupied for several hours	—1	+15
Two occupants, 2 candles, for 15 minutes	—3	+24
Unoccupied for several hours	+7	+19
Unoccupied for several hours	+10	+18

Table 4. Temperatures of domed snow-block shelters and environs (°F.).
Shelter No. 1. built directly on sea ice.
Shelter No. 2 built on snow-drift 18 inches deep.

Date and time	*Shelter number*	*Outside air temperature*	*Wind m.p.h.*	*Subnivean temperature**	*Interior of shelter*		
					Top	*Centre*	*Floor*
Apr. 17, 1956 1930†	1	—5	14	+16	+10	+7	+7
Apr. 19, 1956 1915	1	—2	6	+17	+12	+11	+10
	2	—2	6	+17	+10	+9	+8
	2	(with 1 occupant, door closed)			+19	+20	+18

*At the surface of the sea ice beneath 14 inches of snow.

† One hour after construction.

amounts of heat. Since there is probably little convection inside a shelter the major avenues by which an occupant can loose heat are radiation to the walls and conduction to the floor. With respect to the radiation from the surface of a clothed person snow is essentially a black body. Heat losses by this path could therefore be reduced by shielding the walls. The most effective shield would be a material of low emissivity, such as aluminium foil, but a cloth lining would help materially and is more likely to be available. If the cloth has an emissivity in the infrared region close to unity (essentially a black body) and the temperature difference between inner and outer surfaces is slight (a few degrees), heat loss by radiation will be significantly lowered, depending as it does on the difference of the fourth power of the absolute temperatures of the radiating surfaces. A liner has the additional advantage of reducing glazing of the walls and subsequent loss of insulating efficiency. A cloth liner for snow houses has been described by Turner (1941) and the use of a skin liner for houses by Eskimo by Mathiassen (1928).

Heat loss by conduction to the floor can be reduced by the use of available insulating materials under the sleeping bags. Caribou-skin sleeping pads have, of course, a long history. Heat loss is relatively high when an air mattress alone is used, probably because of convection and radiation losses through the mattress. This can be substantially reduced by placing clothing or other insulating material between sleeping bag and air mattress.

When a snow shelter is heated with a pressure stove ventilation becomes necessary. The hazard of carbon monoxide poisoning can be serious in a poorly ventilated shelter, particularly if the interior has become well glazed. The simple expedient of making a hole in the roof and opening the door is usually sufficient. Stefansson (1944) has described methods of ventilation. The factors involved in carbon monoxide poisoning in snow shelters have been discussed by Henderson and Turner (1940); Irving, Scholander, and Edwards (1942); and Scholander, Irving, and Edwards (1943).

Whereas most of the comments of this discussion apply particularly to regions of extreme cold, the snow house is not without virtue in more temperate climates. The snow cover in the Cascade Mountains of Washington, for example, is very deep and has a relatively small temperature gradient. The snow is often suitable for snow-block or cave construction. The air temperatures are generally a few degrees below freezing and occasional periods of thaw occur. Building snow shelters and living in them is therefore sometimes an unpleasantly wet occupation. With carefully insulated floors and the use of liners snow-block shelters or snow caves can be excellent even in this climate.

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