

# The Shelter Characteristics of Traditional-Styled Inuit Snow Houses

G. PETER KERSHAW,<sup>1</sup> PETER A. SCOTT<sup>2</sup> and HAROLD E. WELCH<sup>3</sup>

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**ABSTRACT.** The shelter value of snow iglus at Resolute (74°41'N, 94°54'W) in the Canadian High Arctic was assessed. After a survey of snow conditions, construction sites were chosen and two iglus were built and furnished in a traditional way. A large iglu (4.1 m diameter) contained 72 blocks averaging 23.6 kg and had a surface area-to-volume ratio of 2.21:1. A smaller iglu (3.05 m in diameter) contained 46 blocks averaging 28.2 kg and had a surface area-to-volume ratio of 1.73:1. The smaller iglu provided 75% of the large iglu's space for 76.5% of its mass. Snow hardness averaged 12 000 g·cm<sup>-2</sup>, and the mean density of the snow was 397 kg·m<sup>-3</sup>. The energy required to build and heat each iglu was calculated from the snow characteristics, construction activities, and microclimate parameters measured during occupancy. Heat flux was calculated for human bodies, *kudliks* (seal oil lamps), and geothermal sources at temperature differentials as high as 45°C from ambient, for both the unlined large iglu and the small iglu, which was lined with caribou skins on the inside. The smaller iglu was more energy efficient, requiring the fat of one seal every 6.3 days for heating, while the larger iglu required the fat of one seal every 3.7 days. The meat content of each seal would have sustained a family of four for the same time interval, and the resultant body heat would have provided 8% to 14% of the total energy necessary to maintain comfortable temperatures within the iglu.

**Key words:** iglu, snow house, winter shelter, Inuit, snow dwelling, traditional winter houses

**RÉSUMÉ.** On a évalué la valeur de la protection offerte par les igloos de neige à Resolute (74° 40' de latit. N.) dans l'Extrême-Arctique canadien. On a d'abord procédé à un relevé de l'état de la neige, puis choisi les sites et construit et équipé deux igloos de façon traditionnelle. Soixante-douze blocs de neige pesant en moyenne 23,6 kg ont servi à construire le grand igloo (4,1 m de diamètre) dont le rapport surface:volume était égal à 2,21. Quarante-six blocs pesant en moyenne 28,2 kg ont servi à la construction du petit igloo dont le rapport surface:volume était égal à 1,73. Ce petit igloo représentait 75 p. cent de l'espace du grand igloo pour 76,5 p. cent de sa masse. La dureté de la neige était en moyenne de 12 000 g·cm<sup>-2</sup> et sa densité moyenne de 397 kg·m<sup>-3</sup>. On a calculé l'énergie nécessaire pour construire et chauffer chaque igloo à partir des caractéristiques de la neige, des activités relatives à la construction et des paramètres du microclimat mesurés au cours de l'occupation. On a calculé le flux thermique pour les corps, les *kudliks* (lampes à l'huile de phoque) et les sources géothermiques à des différences de température allant jusqu'à 45 °C au-dessus de la température ambiante, et ce, pour le grand igloo nu et pour le petit qui, lui, était tapissé de peaux de caribou sur les parois internes. Le petit igloo était le plus éconergétique, ne consommant pour le chauffage que la graisse d'un phoque tous les 6,3 jours alors que le grand igloo en consommait autant tous les 3,7 jours. La viande de chaque phoque aurait assuré la subsistance d'une famille de quatre personnes au cours des mêmes périodes, et la chaleur animale qui en aurait résulté aurait fourni de 8 à 14 p. cent de l'énergie totale nécessaire pour maintenir une température confortable dans l'igloo.

**Mots clés:** igloo, maison de neige, abri hivernal, habitation de neige, Inuit, maisons d'hiver traditionnelles

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## INTRODUCTION

Igloos, or *iglus*, as we prefer it (spelling and definition follow Stefánsson, 1944), have long been associated with the Inuit (Mathiassen, 1928; Stefánsson, 1944), who still use them for temporary shelter while travelling. The snow blocks used to construct these shelters provide insulation and eliminate the influence of wind on the loss of body heat. The shelter significance of iglus is highlighted by Jumikis (1966), who cautioned that too thick a block provides too much insulation and risks excessive heating that could cause melting.

However, the insulating characteristics of the snow blocks vary with weather conditions, the time of year, and their locations throughout the Arctic.

While iglus have numerous designs, architecturally they are often incorrectly portrayed as hemispheric domes. This form is structurally unstable, since the walls would tend to spread outward until they failed (Handy, 1973). In reality the iglu shape is best described as an inverted paraboloid or a catenoid in which the compressive forces increase toward the base of the structure, ensuring structural integrity (Handy, 1973).

<sup>1</sup> Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta T6G 2E3, Canada

<sup>2</sup> Department of Biological Sciences, University of Alberta, Edmonton, Alberta T6G 2E9, Canada

<sup>3</sup> Department of Fisheries and Oceans, Central and Arctic Region, Freshwater Institute, 501 University Crescent, Winnipeg, Manitoba R3T 2N6, Canada

TABLE 1. Comparisons of iglu architectural characteristics and temperature data.

Source	Interior Dimensions		Temperature (°C)					Remarks
	Diameter (m)	Height (m)	Exterior	Platform	Door well	Roof apex	Chamber centre	
Elsner and Pruitt (1959)	2.32	1.52	-18.9	-13.3	nd <sup>1</sup>	-12.2	-13.3	No heat source or occupants
Hall (1879)	3.2	nd	est. -57.8	5	nd	nd	nd	three <i>kudliks</i> , 17 people
Mathiassen (1928)	4.1	2.45	-34	-3.1	-6.0	nd	1.6	multiroomed, four <i>kudliks</i>
Mathiassen (1928)	nd	nd	-10	4.2	0.0	nd	6.4	large, skin-lined, two <i>kudliks</i>
Mathiassen (1928)	nd	nd	-30	5.2	0.5	nd	9.8	small, skin-lined, two <i>kudliks</i>
Mathiassen (1928)	nd	nd	-41	-1	-7.0	nd	4.0	not skin-lined
Parry (1824) in Mathiassen (1928)	nd	nd	-32	-5 to 0.0	nd	nd	nd	several <i>kudliks</i> , many people and dogs
Rasmussen (1931)	4.4	2.3	nd	nd	nd	nd	nd	two adults, three to four children
Stefánsson (1944)	nd	nd	-45.6	-6.7	-40	13.9	2.8	heat source

<sup>1</sup> nd = no data

The shelter value of iglus is experientially known to northern peoples, but few formal quantitative studies are available to provide objective support for this traditional knowledge. Studies vary from historical anecdotes to numerical data, but most sources lack enough information to calculate, for example, the insulation value of the snow. Snow block dimensions have been reported (e.g., Rowley, 1938), but snow density data are lacking. Several earlier researchers described conditions in iglus with sporadic temperature data (Table 1), while others have reported only dimensions (e.g., Rasmussen, 1931) or described temperatures but not the size of the structure (e.g., Gabus, 1940). A description of arctic voyages from 1821 to 1825 recounts iglu dimensions of 2.5 to 4.6 m diameter and 2.7 to 3.1 m high, constructed of blocks 0.61 m long and 0.15 m thick (Anonymous, 1831). Hall (1879) reported a winter dwelling 3.1 m in diameter in which the 38 blocks were 0.61 to 0.76 m long and 0.48 m high in the main structure. A “travelling” iglu also reported by Hall (1879) was 3.22 m in diameter and housed 17 people while they were travelling. The lining of the inside of the iglu with skins, practised on Baffin Island and in the Iglulik area (Lyon, 1824), brought the inside chamber temperature up from 1–3°C to 10–20°C (Boas, 1888; Mathiassen, 1928).

In addition to snow conditions and dimensions, modifications made to the structure after construction will cause variation in the thermal characteristics of iglus. For example, the entry position and dimensions and the nature and positioning of bedding, as well as the use of skin lining, will change the insulating characteristics (Boas, 1888; Mathiassen, 1928). Historically, heat and light in an iglu were provided by burning animal fat (mostly from seals) in *kudliks*. These soapstone heaters or lamps varied considerably in size, from 12 cm up to 136 cm in total length (Jenness, 1946). The smaller lamps were used in temporary shelters when travelling, whereas the larger lamps, typically not less than 60 cm long, were used for heat and lighting in semipermanent winter dwellings. Consequently, regional differences in construction design and furnishings also make it difficult to assess the shelter value of iglus reported in the literature.

The objective of this study was to quantify the shelter value afforded by iglus that were constructed using traditional techniques. Steltzer (1981) provides good photographic

documentation of iglu-building procedures, while Yue and Yue (1988) provide an entertaining and readable account of traditional iglu construction and use. Both these publications provide details of construction similar to those employed in this experiment. Structures were designed to simulate two situations: first, a larger iglu similar to what might have been occupied for extended periods at a seasonal base, and second, a smaller iglu such as might have been used for short periods on hunting expeditions or when travelling (Figs. 1 and 2). *Kudliks*, candles, and a naphtha lantern were used for heat and lighting during occupancy. Temperatures and heat flux were monitored under a variety of conditions, and energy requirements in terms of seal fat biomass were determined.

## METHODS

The study was undertaken during mid-winter (February 1993) in the High Arctic at Resolute (Qausuittuq) N.W.T. (74°41'N, 94°54'W) at Fisheries and Oceans Canada's, Resolute Marine Laboratory. A 2 × 2 km section of typical terrain was surveyed to assess snow conditions. From a central point, snow depth was measured along five radii placed approximately 75° apart. On each transect, snow depth was measured with a metre stick once every 10–20 m for at least 50 points. The density of the snow surface was determined at random points along the transects using three samples taken with a 200 cm<sup>3</sup> (4.75 × 7 cm mouth) box-type snow cutter. Three samples at each of 12 sites were aggregated to measure snow density. For comparison, snow depth and density were determined at the Atmospheric Environment Service snow course during the same day, and the long-term snow data for Resolute were acquired from the Atmospheric Environment Service archives in Downsview, Ontario.

The main construction site was an open area 100 m east of the laboratory facility, where drifts were large enough to provide building materials. The drifts in this area were largely formed from a single storm and thus were suitable for iglu building (Boas, 1888). The resulting snow, lacking layers and discontinuities, was relatively uniform in density and hardness, and therefore lacked structural weaknesses that could cause the snow blocks to break. Snow depth was measured at

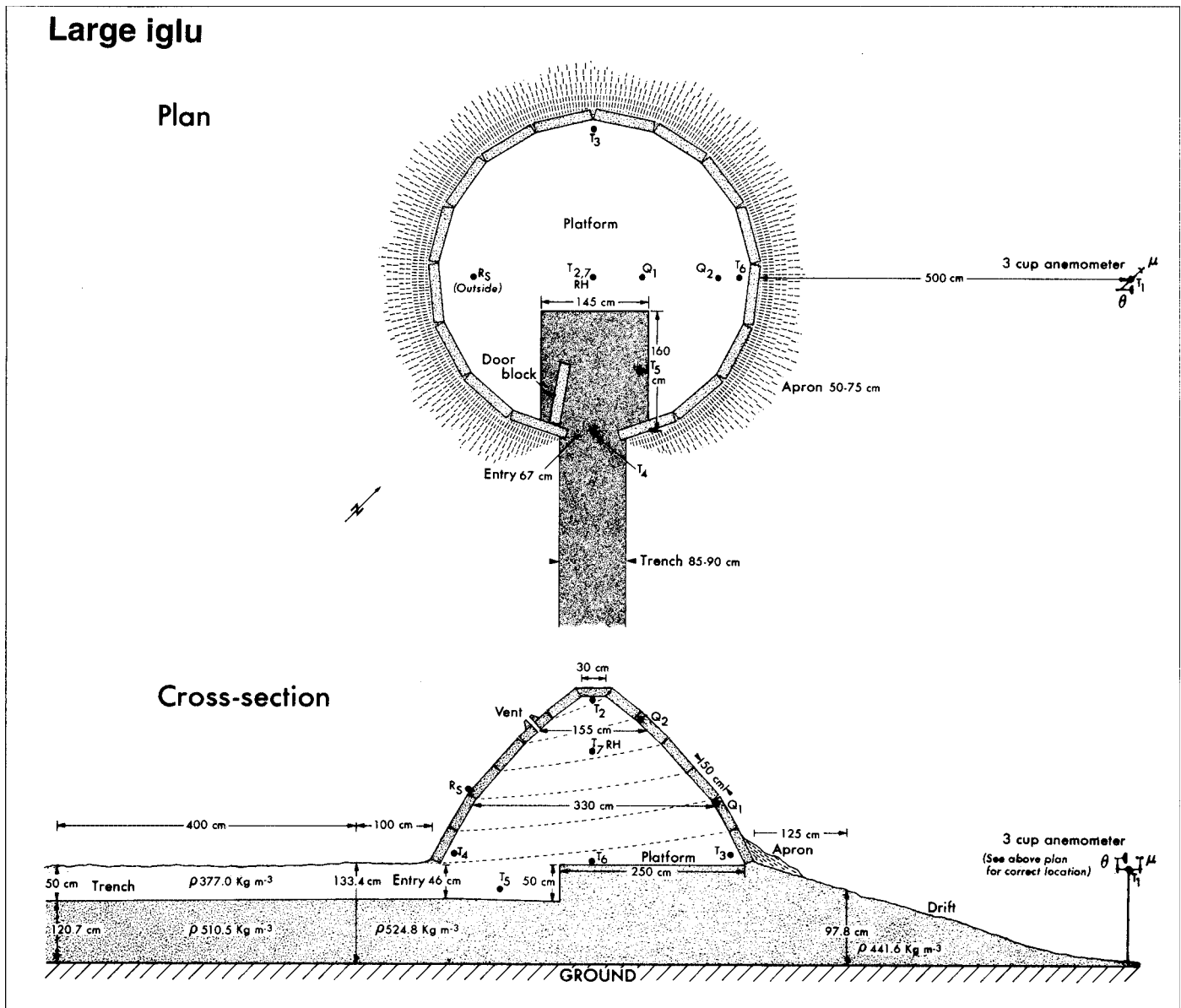


FIG. 1. Cross-sectional and plan view of the large experimental iglu. The anemometers were at the level of the iglu, not off the drift and below the iglu as depicted. The illustrated notches between snow blocks were packed full of snow during the chinking after the key block was placed.  $T_1$  to  $T_7$ : temperature sensors (thermocouples), RH: relative humidity sensor,  $R_S$ : solar radiation sensor (pyranometer),  $\mu$ : wind speed sensor (anemometer),  $\theta$ : wind direction sensor (wind vane),  $Q_1$  to  $Q_3$ : heat flux sensor (heat flux plate).

1 m intervals, and total snowpack density of the drift was measured with a Meteorological Service of Canada snow sampler. A 6% error has been reported for this unit (Goodison et al., 1981); however, at Resolute the snow was so well packed that little loss from the tube was possible, so error from losses in extracting the corer from the snowpack was probably smaller. During construction and later in situ the density of the snow blocks was determined by sampling with a 200 cm<sup>3</sup> box-type snow cutter, again by weighing aggregates of three samples. Snow densities were determined at 1 m intervals along the construction trench as well as from upper and lower blocks and the sleeping platform in the small iglu after it was inhabited. Snow hardness was assessed by hand-held gauges called spring penetrometers (Adams and Barr, 1974). Thirty points were sampled at random along the

trench walls at each iglu site after removal of the snow blocks, and 20 points were sampled on the iglu; thus, 50 hardness values were determined for each iglu.

The construction technique followed well-known traditional procedures learned from the Inuit and practised over the years by H.E. Welch. At each site, snow blocks cut vertically with a carpenter's saw were removed to form a trench that became the entrance to the iglu. Once the trench was started, a long block was suspended across it, and the tops of the first few blocks on the wall base were trimmed to angle upwards at approximately 30°. This angle dictated the nature of the spiral of blocks as subsequent levels were added atop the set of base blocks. Later the gaps between the blocks were chinked with loose snow, and around the base of the wall on the outside, an apron of loose snow was mounded against the

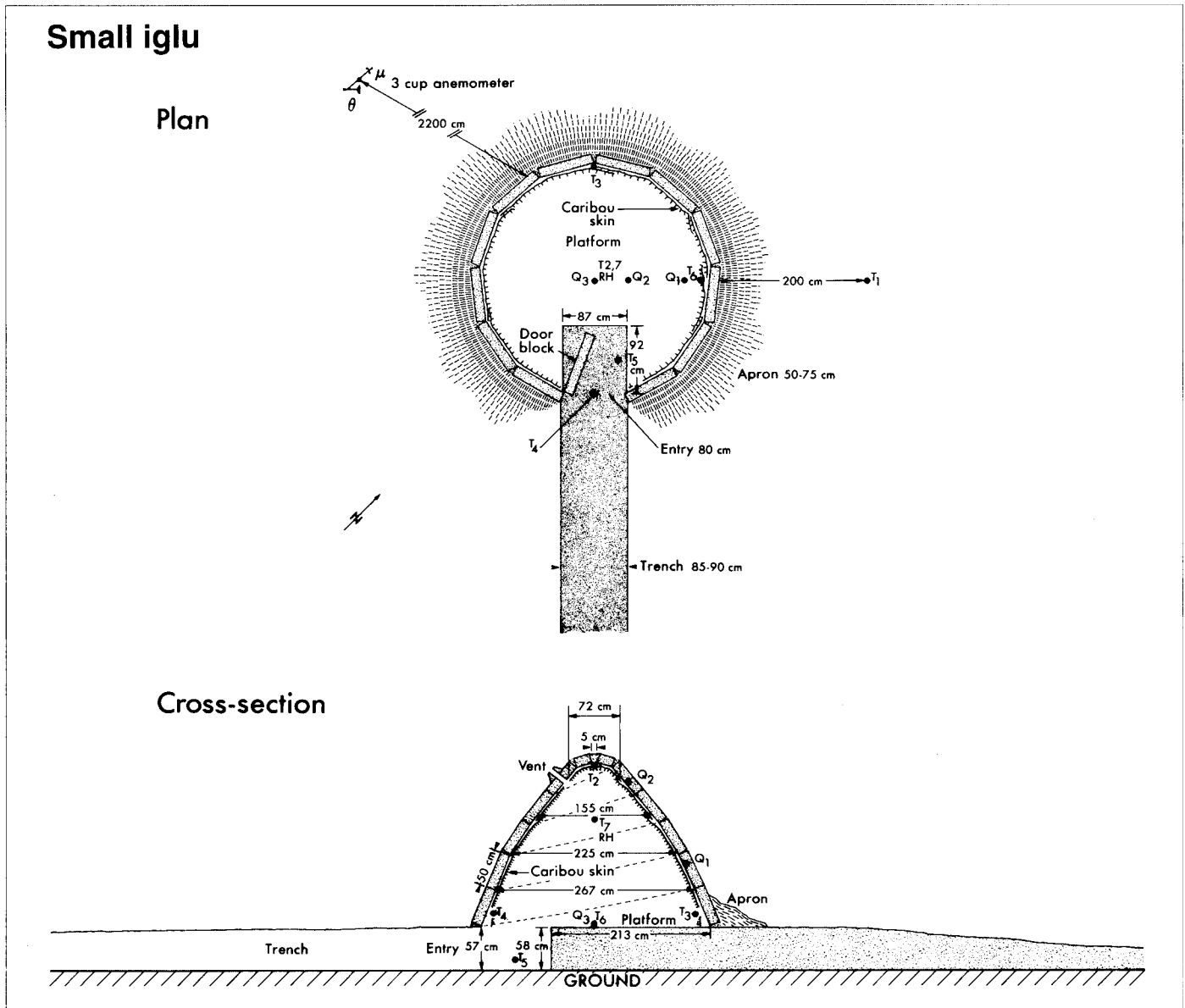


FIG. 2. Cross-sectional and plan view of the small experimental iglu. The anemometers were at the level of the iglus, not off the drift and below the iglu as depicted. The illustrated notches between snow blocks were packed full of snow during the chinking after the key block was placed.  $T_1$  to  $T_7$ : temperature sensors (thermocouples), RH: relative humidity sensor,  $R_s$ : solar radiation sensor (pyranometer),  $\mu$ : wind speed sensor (anemometer),  $\theta$ : wind direction sensor (wind vane),  $Q_1$  to  $Q_3$ : heat flux sensor (heat flux plate).

wall up to 10–15 cm. Inside each iglu, the configuration of the sleeping platform, placement of *kudliks*, design of the skin lining, and other details followed the advice of Resolute residents who had routinely lived in iglus in the High Arctic. Calculation of interior wall surface area and chamber volume was adapted for the unique cross-sectional shape of each iglu. Consequently, calculations for the larger iglu were made with a succession of conical fusta, while for the smaller iglu, a second-order polynomial was fitted and analytically integrated (D. Fenna, pers. comm., 1995).

Heat was provided by burning oil in traditional-style seal oil lamps, or *kudliks*. The *kudliks* used in the experiment differed in size (the burning wick lengths were 35 and 58 cm) and composition (the smaller one was metal, while the larger was of soapstone). The longer the burning wick, the greater

the heat generated. The stone *kudlik* had been used in iglus and other dwellings in the Pond Inlet region for many years. The steel *kudlik* was fabricated from the top of an oil drum, but with the same shape and design as a traditional stone *kudlik*. The fuel was seal oil, which was prepared by pounding frozen seal fat before inserting it into the well behind the wick. The heaters were set atop three wood pegs inserted in the platform to provide 15 cm legs. For short periods a Coleman brand naphtha lantern and candles were used to provide additional lighting.

The smaller iglu was lined on the second night of use (25–26 February). A single layer of caribou winter skins with the hair facing the chamber side (Fig. 2) was hung on cords passed through the wall and held in place by small wooden toggles on the outside of the structure. The skins were

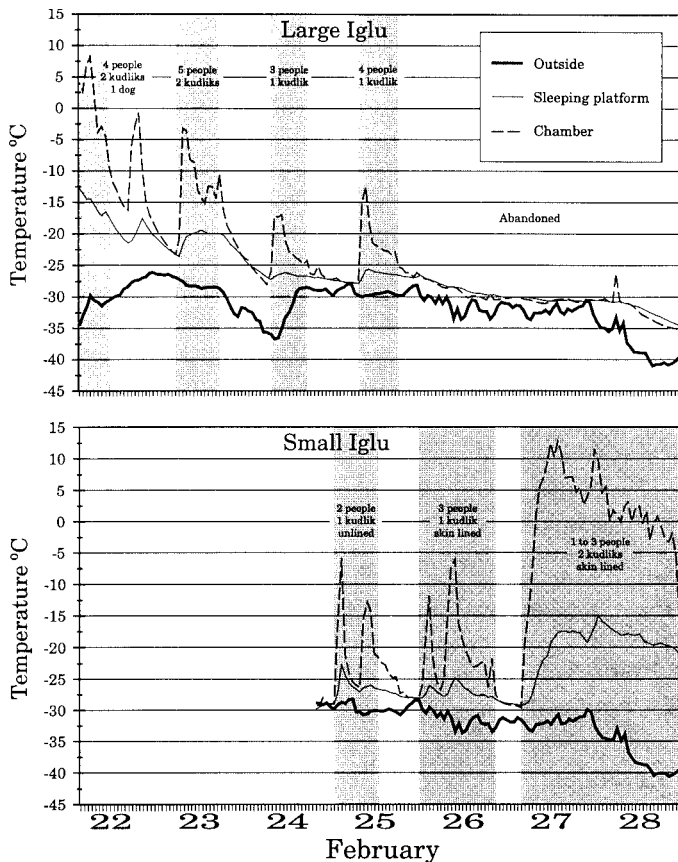


FIG. 3. Temperature characteristics of the large and small iglus over the study period. Each structure was occupied over four successive nights and then abandoned (the large iglu on the morning of 25 February and the smaller iglu on 28 February 1993). The number of occupants and *kudliks* varied.

overlapped but not sewn together. The sleeping platforms were covered with one layer of caribou skins (winter hides with hair on) and, on several nights, with 5 cm thick foam sleeping mats. People entered the iglus at approximately 2200 and used the *kudlik*(s) until approximately 2400 each time. The larger iglu was occupied for sleep periods on four successive nights (Fig. 3). The number of occupants varied between three and five, while the number of *kudliks* varied from one to two. The smaller iglu was occupied for similar periods on four successive nights, and was heated continuously over the last 40 hours of the experiment. One to three occupants slept in the small iglu using either one or two *kudliks*. The door opening was sealed with a snow block (Figs. 1 and 2), even when the iglu was not in use.

Both iglus were instrumented with Campbell Scientific International (CSI) CR10 microloggers (Figs. 1 and 2). Sensors attached to the loggers included type "T" thermocouples; a CSI HMP35C temperature and relative humidity (RH) sensor (Vaisala capacitive relative humidity sensor and a Fenwal Electronics UUT51J1 thermistor); Radiation and Energy Balance Systems Inc. HFT-1 soil heat flux plates; R. M. Young Wind Sentry (03001-5) wind vane and anemometer (offset of  $0.2 \text{ m}\cdot\text{s}^{-1}$ ); and a LI-COR (LI-200SZ) pyranometer. Temperatures were taken 5 m outside the iglu at 1.10 m height, inside the door opening within the door well,

at the top of the door well, 10 cm above the door, at the rear of the sleeping platform, at the edge of the sleeping platform, approximately 75 cm below the apex of the roof, and at the roof apex. The temperature/RH sensor was located 75 cm below the apex of the roof. The heat flux plates were located at approximately 80 cm and 190 cm above the platform within the east wall, at a depth of 5 cm measured from inside the iglu.

Sensors were read every 10 seconds, and hourly and daily means and maximum and minimum values were calculated. Heat sums were calculated daily by accumulating hourly mean values above  $0^\circ\text{C}$ . Average hourly heat flux values for each iglu were calculated from the hourly average values from the two wall-mounted plates. Once the wall surface area was calculated, this value was multiplied by the average hourly heat flux to obtain total hourly values of energy loss from each iglu.

## ANALYSIS AND RESULTS

### Weather Conditions

During the experiment, the ambient air temperature ranged from  $-28.2^\circ$  to  $-41.1^\circ\text{C}$ . The coldest period occurred at the end of the study, while the warmest was shortly after the initiation of the project (Fig. 3). Wind speed averaged  $2.9 \text{ m}\cdot\text{s}^{-1}$  over the period of the study, with maximum speed of  $9.3 \text{ m}\cdot\text{s}^{-1}$  recorded at 1900 on 24 February. The first two days of the study were the calmest, but the wind averaged  $3.0\text{--}4.5 \text{ m}\cdot\text{s}^{-1}$  for the last four days of the experiment. There were no measurable winds inside the iglus, since the doors were on the lee side of the structure (Figs. 1 and 2).

### Regional Snow Conditions

There was an average of 9.2 cm of snow on the ground (range 0–62, SD 4.35). At the Atmospheric Environment Service site, the 10 snow samples averaged 10.9 cm depth (range 3.8–24.1, SD 7.2). The snow density averaged  $363 \text{ kg}\cdot\text{m}^{-3}$  (range 275–430, SD 44.0). Over the 37 years prior to 1993, an average of 25.1 cm of snow had accumulated by the sample date (1 March); in only two other years had less than 11 cm accumulated. Of the 250 points where snow depth was measured, 22% were bare and only 5.6% had accumulations deeper than 30 cm. Of the drifts found in the  $4 \text{ km}^2$  area, only two, representing 3.6% of the area, were sufficiently large to permit the construction of an iglu.

The drift used for iglu construction had two ridges where approximately  $9 \times 22 \text{ m}$  of snow was deeper than 30 cm. An area of  $5 \times 22 \text{ m}$  had sufficient snow to cut a 50 cm high block. The maximum depth was 109 cm.

### Properties of Snow Blocks

The large iglu required 72 blocks and enclosed a volume one-third greater than that of the smaller iglu (Tables 2 and 3), which required 46 blocks. The snow blocks averaged 14.7 cm

TABLE 2. Architectural comparisons of the two test iglus, Resolute, Northwest Territories.

	Chamber			volume (m <sup>3</sup> )	Door opening area (m <sup>2</sup> )	Door well volume (m <sup>3</sup> )	Platform	
	max. diameter (m)	max. height (m)	wall area (m <sup>2</sup> )				height (m)	area (m <sup>2</sup> )
Large iglu	4.10	2.25	22.83	10.32	0.308	1.16	0.50	10.56
Small iglu	3.05	2.18	13.41	7.76	0.456	0.464	0.57	8.91

TABLE 3. Snow characteristics of the two test iglus, Resolute, Northwest Territories.

	Number of blocks	Snow hardness (g·cm <sup>3</sup> ) (n = 30)	Snow density (kg·m <sup>3</sup> ) (n = 10)	Snow volume (m <sup>3</sup> )	Mean block mass (kg)	Total mass (kg)	Person-hours of work
Large iglu	72	11 000 ± 1500	377.0	4.5	23.56	1696.5	9
Small iglu	46	12 500 ± 500	416.4	3.2	28.24	1299.2	7

thick (n = 40, SD 1.72) and were initially 50 cm high by 75 cm long. Because they were trimmed to interlock, their height and final length varied considerably from the base of the wall to the top. The densities of the snow blocks cut for the large iglu were slightly greater (4%) than the regional average of 363 kg·m<sup>-3</sup>. The hardness averaged 11 000 g·cm<sup>-2</sup> (range 9000 to 12 500 g·cm<sup>-2</sup>). The snow densities and hardness values were somewhat higher for the small iglu (416 kg·m<sup>-3</sup> and 12 000 g·cm<sup>-2</sup> with range 11 000 to 12 500 g·cm<sup>-2</sup> respectively). During use of the smaller iglu, the block density increased to an average of 430 kg·m<sup>-3</sup> (range 419 to 446).

#### Work Involved in Construction

The volume and mass of snow required for the smaller iglu were 71% and 76.5% respectively of the requirements for the large one (Table 3). The blocks were lifted 0.5 m from the trench to the iglu base plus 1.0 m above the base for placement. Multiplying this distance by the total mass of the snow blocks will give mass moved per metre during the construction. Thus, for the large iglu:

$$(0.5 \text{ m} + 1.0 \text{ m})(1696.5 \text{ kg}) = 2.54 \cdot 10^3 \text{ kg} \cdot \text{m}^{-1} \quad [1]$$

If 1 kg·m<sup>-1</sup> = 98.07 J, then 2.54·10<sup>3</sup> kg·m<sup>-1</sup> = 249.10 kJ. If 1 kW·h = 3600.54 J, then the energy used to lift the blocks for the big iglu would be:

$$(249.10 \text{ kJ} / 3600.54 \text{ J}) = 69.18 \text{ kW} \cdot \text{h} \quad [2]$$

The ratio of the heat equivalent of work to the heat equivalent of metabolism during work, or gross efficiency, is approximately 20% for humans, or slightly lower if increased metabolism during recovery is also considered (Kleiber, 1975). The metabolic demand of lifting the iglu blocks during the two-hour construction period of the large iglu would be:

$$(69.18 \text{ kW} \cdot \text{h}) (20\%) = 13.84 \text{ kJ} \cdot \text{h}^{-1} = 3305 \text{ Kcal} \quad [3]$$

An active Inuk requires approximately 12.56 kJ·d<sup>-1</sup> (3000 Kcal per day) (Kemp, 1971; Kleiber, 1975), so iglu construction

should roughly double the daily energy expenditure (~210%). Subjectively, lifting 72 snow blocks averaging 24 kg is strenuous labour. The cutting, breaking out, trimming, transporting, and chinking is very strenuous also. If environmental conditions were severe (e.g., strong winds and low temperatures), then additional energy costs would be incurred.

#### Temperature Characteristics

Iglu temperatures were higher than outside temperatures even without heating (Fig. 3); however, the difference from ambient temperature was least after abandonment (Fig. 4). Inside temperatures declined slowly after the *kudlik*(s) were extinguished at the beginning of each sleep period and also after people left the structure during the day (Fig. 3). In the large iglu, the greatest difference from ambient temperature occurred early in the experiment, when both *kudliks* were burning and four adults and a dog occupied the iglu (Fig. 4). The only time when the temperature at the rear of the platform exceeded chamber and ceiling temperatures was when the dog was sleeping next to the sensor. Otherwise, the warmest temperatures were recorded near the ceiling and within the upper portion of the chamber (Fig. 4). The warmest nights inside the large iglu were experienced when one of the *kudliks* was tended throughout the night (21–22 February, Fig. 3). In the small iglu, the ceiling sensor was behind the caribou skins after their installation (Fig. 2). It consistently recorded temperatures lower than those in the chamber (the reverse of the large iglu, where skins were not deployed on the walls) (Figs. 1, 2, and 5). The greatest temperature gradient across the skin lining was 4.9°C. It occurred shortly after the skin was hung, while two *kudliks* were burning. Consequently, a pattern of temperature change similar to that of the large iglu was evident in the smaller iglu, except that the differences from outside temperature were greater because of the insulating skins and the smaller chamber volume (Fig. 6). However, during the final 40 hours, the *kudliks* and skin insulation produced the warmest and most uniform temperatures experienced in the small iglu during the experiment (Figs. 3 and 4).

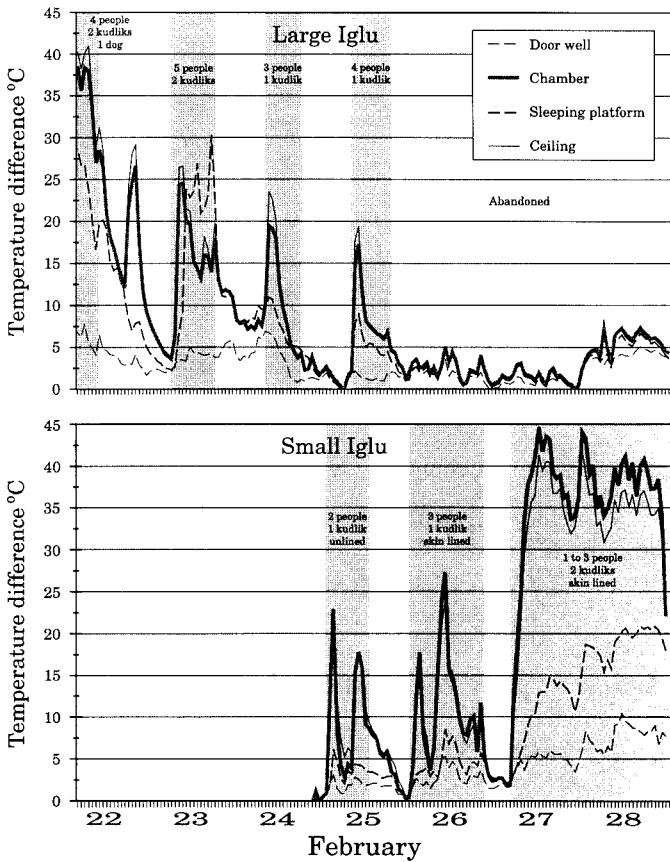


FIG. 4. Differences between outside (ambient) temperatures and various locations within the two iglus. With few exceptions, all locations within the iglus were warmer than outside, even when no heat source existed in the iglu.

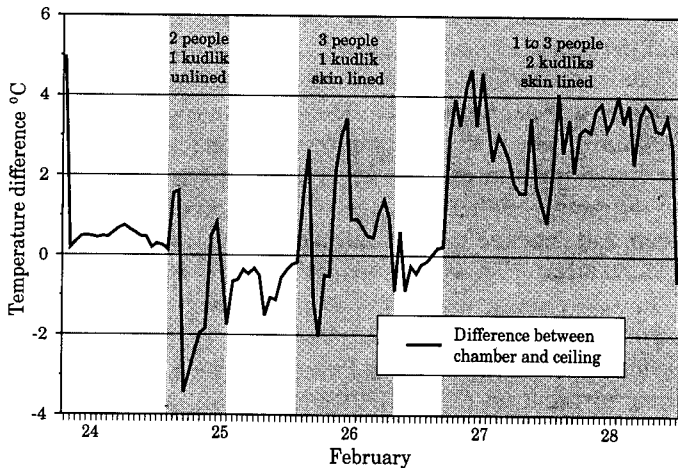


FIG. 5. Difference in temperature between the chamber and the air space behind skins below the snow dome in the small iglu induced by caribou skin insulation. Positive values indicate the degree to which iglu chamber temperatures were warmer than the air space between the skin and the iglu wall; negative values mean the chamber was colder.

Energy Characteristics

Heat flux values measured at two heights on the inside of each iglu (Figs. 1 and 2) reflect heat losses from sources within the iglu. There were three heat sources: the kudlik(s),

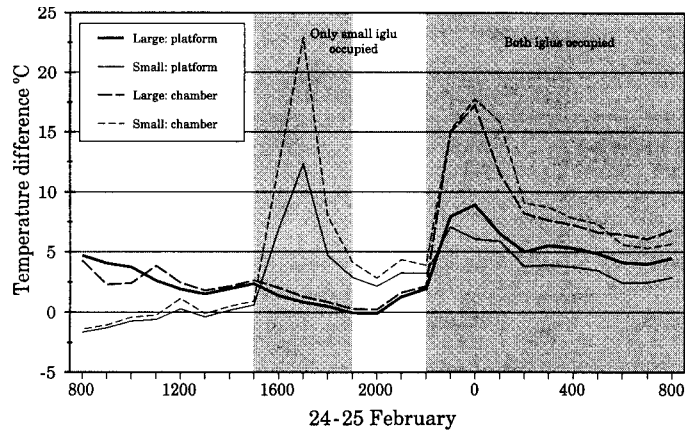


FIG. 6. Temperature differences using ambient outside temperatures for comparison during the 24-hour period when both the large and small iglus were occupied. The first warm period beginning at 1600 in the small iglu reflects the use of a kudlik at that time. Both iglus were occupied from 2300 to 0800. During that time, temperature differences between the iglus varied, but not consistently.

the occupants, and any geothermal heat emitted from soil beneath the iglu. Occupants used insulated clothing or sleeping bags to reduce body heat loss to the air within the iglu chamber.

Heat flux from the iglus was greatest when the heat was generated from all three sources (Fig. 7). Maximum values were  $-75 \text{ W}\cdot\text{m}^{-2}$  in the large iglu and  $-129.6 \text{ W}\cdot\text{m}^{-2}$  in the small one. The continuous occupation and heating in the small iglu for the last 40 hours of the experiment produced very high flux and total values; however, during the night of 25–26 February, when both iglus were in use, the smaller shelter had substantially lower total energy loss (Fig. 7). At that time the skin liner had not been installed, and the main difference between the structures was the wall surface area and chamber volume (Table 2).

DISCUSSION

Snow Conditions

In the polar desert, snowfall is low (Maxwell, 1980), and snow is redistributed on the surface by wind, forming snow-free areas adjacent to thick drifts (McKay and Gray, 1981). The snow accumulations that occur on sea ice are greatest where drifts form in the lee of ice surface irregularities such as those formed by pressure ridges, multiyear ice, or icebergs. Thus, access to snow suitable for iglu construction can be uneven across the landscape. Furthermore, snow with thickness, density, and hardness characteristics suitable for iglu construction can be scarce in early winter, in years of low snowfall, or at times when winds are too light. Tundra snowdrifts have average densities  $> 300 \text{ kg}\cdot\text{m}^{-3}$  (McKay and Gray, 1981). As density increases, insulative capacity declines (Langham, 1981). The search effort expended to locate suitable snow can be considerable when winter conditions are less than optimum. In the Arctic it is possible that during periods when access to suitable iglu construction materials

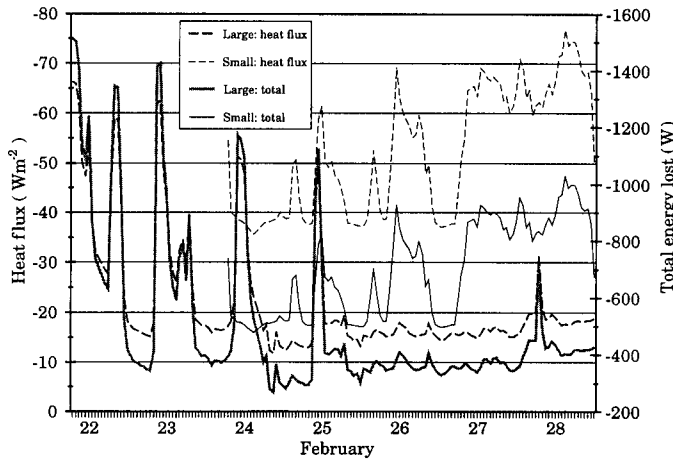


FIG. 7. Heat flux from different-sized iglus is minimal when the structures are unoccupied but increases greatly with a heat source. Total energy lost is the product of area and hourly heat flux calculated for each iglu.

was limited, there may have been considerable stress on human populations.

*Work Involved in Construction*

The only known historical record of the time required to build an iglu was reported by Boas (1888). He stated that a 1.5 m high, 2.1 m diameter, 25-block travelling iglu could be built by two people in two hours (a rate of 6.25 blocks per hour per person). With three people, our averages were 8 and 6.57 blocks per hour per person for the large and small iglus respectively. However, the time required to initiate the block cutting and lower wall assembly is similar regardless of the iglu size; consequently, the larger structure should have taken less time per block to assemble. Nevertheless it is noteworthy that time commitments for the construction of our experimental iglus were similar to what was reported more than 100 years earlier, suggesting that our technique approximates that of traditional times. The energy expended in construction is significant: block lifting alone amounted to 210% of the mean daily expenditure, effectively doubling the energy requirements for the average Inuk. When block lifting is shared between a person cutting and a person placing the block, for example, the energy expenditure is split between two people. However, activities such as cutting, fitting, and chinking add considerably more energy expenditure during construction.

*Temperature Characteristics*

The elevation of chamber temperature by 5°C above ambient in the unoccupied, larger iglu can be attributed to geothermal rather than solar heat sources, since there was no pattern of diurnal temperature or heat flux coinciding with the daily photoperiod. This 5°C elevation was higher than expected, since the Resolute area is underlain by continuous permafrost to a depth of 380 to 600 m and has a mean annual soil surface temperature of -12°C (Taylor et. al., 1981).

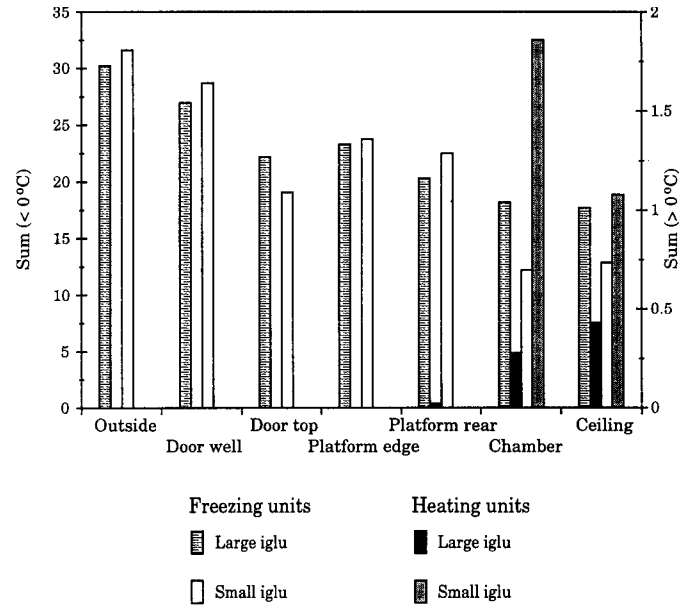


FIG. 8. When we consider only the record period during which the iglus were in use, it is evident that the smaller, insulated iglu was much warmer. This can be partly explained by the continuous use of *kudliks* during the last 40 hours of the experiment. Freezing and heating units are the accumulated hourly mean temperatures below and above freezing respectively, during the period of occupancy.

The addition of heat in the iglus elevated the chamber temperature by as much as 45°C above ambient conditions. This difference, greatest in the smallest structure, was enhanced by the addition of an insulating layer of hanging caribou skins (Figs. 4 and 6). Differences in shape gave the larger iglu 70% more wall area but only 33% more chamber volume (Table 2) than the smaller iglu, so the larger iglu required greater heat inputs to elevate chamber temperatures above 0°C (Fig. 3). The surface area-to-volume ratios were 2.21:1 and 1.73:1 for the large and small iglus respectively. Thus the smaller structure was the more efficient shelter (Fig. 8), requiring less heat input to provide more comfortable temperatures for occupants.

During most of the experiment, heat production in the iglus was restricted to the beginning of sleep periods. Consequently, times were too short to achieve steady-state conditions except during the last two days in the small iglu, when the heat flux remained relatively constant (Fig. 7). Otherwise, the maximum temperatures occurred during the pre-sleep periods when the *kudliks* were in use. Historically, iglus in a base camp situation would have been occupied day and night; thus, chamber temperatures would have been maintained well above ambient and generally above 0°C. The continuous heating in the small iglu over the last two days of the experiment was a more realistic test of the shelter value of iglus, since heating was more constant. Comparison between periodic warming and continuous heating illustrates the extreme variability of the interior temperatures that results from periodic occupancy (Figs. 3 and 4). When heat is generated, an elevation of interior temperatures by at least 20°C above ambient can be expected (Fig. 6). This difference will vary as



the temperature outside changes, so at  $-40^{\circ}\text{C}$  a little heat added to the interior of an iglu will raise interior temperatures well above  $0^{\circ}\text{C}$ ; however, less heat addition would be required with warmer ambient conditions.

### Energy Characteristics

The large iglu averaged  $-10\text{ W}\cdot\text{m}^{-2}$  heat flux when not in use. The fact that solar inputs of energy were low throughout the study period is confirmed by the lack of any diurnal fluctuation in heat flux (Fig. 7). If we use the value  $-70\text{ W}\cdot\text{m}^{-2}$  heat flux as representative during occupancy of the iglus, then geothermal heat input accounted for approximately 14% of the energy generated by heat sources in the iglus (Fig. 7). The geothermal contribution will vary. Iglus in southern areas, for example, have warmer ground temperatures and would have higher geothermal heat flow. Further, the common construction site of sea ice would be much warmer, as the water beneath 1 to 2 m of ice would be approximately  $-1.8^{\circ}\text{C}$ . The geothermal inputs will also be site-specific, as the thickness of the snow base can alter heat flux into the dwelling (Elsner and Pruitt, 1959).

Heat flux was greatest when the interior of the iglu was heated to cause a strong temperature gradient. With both iglus occupied the night of 25–26 February, the heat flux for the smaller iglu exceeded that of the larger; however, once the figure was corrected for surface area, it was clear that the smaller iglu lost less heat. Thus the smaller iglu was the most energy efficient. However, there was a noted increase in block density with time. Consequently, the insulative value of the blocks may decline with degree-hours of use. This fact will influence how long an iglu will be used.

Analysis of the hourly heat flux values from before and after installation of the insulating skins indicated a difference of at least  $50\text{ W}\cdot\text{m}^{-2}$ . This observation was confirmed by temperature differences between the chamber and the wall behind the caribou skin liner, which averaged  $3^{\circ}\text{C}$  when the iglu was in continuous use (Fig. 5). Lower total heat flux for the smaller iglu confirms that it is the more energy-efficient (Fig. 7), and with the skin lining, the difference was more pronounced. The heat flux value of  $-70\text{ W}\cdot\text{m}^{-2}$  converted to the metric standard for building insulation (using  $0.1761\text{ m}^2\cdot^{\circ}\text{C}\cdot\text{W}^{-1}$  to convert to R units and  $5.678\text{ h}\cdot\text{ft}^2\cdot^{\circ}\text{F}$  to convert to RSI units) gives an RSI rating of 2.17, or the equivalent of an insulated 10 cm (or R12) building wall.

### Wind Characteristics

The iglu provides relief from wind and the associated latent heat loss (wind chill). However the snow is not completely impermeable to wind effects, as soot buildup (due to incomplete combustion of the seal fat) was less on the windward side of the iglu. This difference was presumably caused by diffusion of air under pressure through the snow blocks. The combined influence of the 8 cm diameter ceiling air vent, the door opening, and the permeability of the snow leads to exchange of some air, but advection was not sensed

within the chamber. Further, the caribou skin lining restricts air exchange by providing a barrier to air movement between the chamber and the snow blocks. Moisture generated by respiration, cooking, and combustion sublimates onto the inside of the wall. This moisture helps seal the surface by creating a thin, icy layer that would reduce moisture absorption deeper in the snow blocks. This layer would presumably reduce air flow through the wall as ice sealed off pores in the surface of the snow blocks.

### Energy Flow Considerations

Regression of heat flux against temperature differential gives  $2.24\text{ W}\cdot\text{m}^{-2}\cdot^{\circ}\text{C}$ . The temperature of the unoccupied large iglu was  $5^{\circ}\text{C}$  above ambient, and this converts to geothermal heating of  $11.2\text{ W}\cdot\text{m}^{-2}$ . With a mean winter temperature of  $-30^{\circ}\text{C}$ , a temperature increase to  $5^{\circ}\text{C}$  would require  $78.4\text{ W}\cdot\text{m}^{-2}$  ( $35^{\circ}\times 2.24$ ) of non-geothermal heat input (assuming  $1\text{ W} = 1\text{ J}\cdot\text{s}^{-1}$ ,  $\times 60\text{ s} \times 60\text{ min} = 3.6\text{ J}\cdot\text{h}^{-1}$ ) which, when corrected for iglu wall area ( $3.6\text{ J}\cdot\text{h}^{-1}\cdot\text{W}^{-1} \times 13.41\text{ m}^2$ ), would be  $90.8\text{ kJ}\cdot\text{d}^{-1}$  heat input for the small iglu and  $154.6\text{ kJ}\cdot\text{d}^{-1}$  for the large. An average ringed seal (*Phoca hispida*), the major winter prey of precontact Inuit (Kemp, 1984 and others), weighs 36.3 kg and is 40% fat at  $39.56\text{ J}\cdot\text{g}^{-1}$  (Winberg, 1971) for an average energy density of  $19.35\text{ J}\cdot\text{g}^{-1}$  (Welch et al., 1992). The small iglu therefore would require 2.3 kg fat per day or one seal every 6.3 days, and the large iglu would require 3.9 kg fat per day or one seal every 3.7 days. An Inuk requires approximately  $12\,560\text{ J}\cdot\text{d}^{-1}$  for metabolic requirements; consequently, the 21.78 kg non-fat portion of a seal with  $5.9\text{ J}\cdot\text{g}^{-1}$  would provide food for nearly 10 days. Considering that the skin and bones were not eaten, that the indigestible portion would be about 15%, and that some fat was eaten, the food requirements per person would be closer to one seal approximately every 8–9 days. Two Inuit would require the meat from a seal every 4–5 days, and the seal fat would fuel the *kudlik*.

Since people spent most of their time in the iglu in winter, their heat output also warmed the iglu. In our experiment, the body heat generated by each person amounted to  $12\,560\text{ J}\cdot\text{d}^{-1}$  or 13.8% of the non-geothermal heat flow in the small iglu and 8.1% in the large iglu. Using a basic family unit of two adults and a small child (whose heat contribution we will ignore), we calculate that the fat from a seal would last about 7–8 days in the small iglu and 5–6 days in the large, while at the same time food requirements would be a seal every 4–5 days. For long-term occupancy, a nuclear family probably used an iglu at least as large, or a bit larger, than our large (4.1 m diameter) one; the larger the iglu, the greater the need for fat relative to meat. Precontact Inuit kept relatively few dogs, one to three per family (Stefánsson, 1919; Kemp, 1984), but their meat demands must be added (dogs eat mostly meat and offal). Therefore, if total food demands were being met adequately, the use of fat and non-fat portions of seals would approximately balance, and precontact Inuit would have had sufficient fat from their food supply to keep an iglu above freezing day and night.

## CONCLUSIONS

Traditional snow houses used by Inuit provide a wind-free, warm microenvironment under arctic conditions. Geothermal heat flow alone warms the interior on the order of 5°C, depending upon the substrate beneath the iglu. Heat flux through new iglu walls is equal to that of an insulated, standard modern 2 × 4 house wall. The presence of two adults and the burning of 2.3 kg of seal fat a day in a lamp maintains a chamber temperature of about 5°C in an unlined iglu 3 m in diameter at -30°C ambient temperature. An iglu 4.1 m in diameter requires 3.9 kg fat a day. Without dogs, the use of fat in the lamp is approximately balanced by the need for food, the equivalent of a ringed seal every 3.7 to 6.3 days, depending on the size of the iglu. The addition of dogs increases meat requirements and the availability of fat for lighting and heating.

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