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THE MICROCLIMATE OF A TEN-MAN ARCTIC TENT
PART I: A PRELIMINARY INVESTIGATION

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Environmental Protection Section
Protective Sciences Division

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ABSTRACT

Some parameters of the microclimate of a ten-man tent in winter were measured. A living zone of the tent was outlined, and the average living-zone temperature defined. Living-zone temperatures, and temperature distributions produced by standard heating systems under various weather conditions were determined. A minimum safe living zone temperature was derived as well as a minimum temperature for comfort. Ventilation of a well weather-proofed tent was found to be low, and controlled by the restriction on air inflow at the base, rather than on air outflow at the peak. This observation has particular importance in tents with floors. Experiments were performed to determine the effect of the liner on interior temperature levels, the effect of a lowered ceiling, and of adding a stack to a heater and venting the exhaust products. Carbon dioxide and monoxide levels were measured, as was the dew point of the air at several levels in the tent.

RÉSUMÉ

On a measuré lors de la saison hivernale quelques paramètres microclimatiques d'une tente pouvant loger dix personnes. La zone habitable a été délimitée et sa température moyenne précisée. On a déterminé dans diverses conditions météorologiques les températures dans la zone habitable ainsi que leur distribution dans cette zone lorsque le chauffage était assuré par un système courant. On a établi à partir de cette expérience la température minimale nécessaire à la sécurité et celle nécessaire au confort. On a constaté que l'aération d'une tente bien isolée contre le froid était faible et qu'elle était réglée en modificant l'entrée d'air à la base de la tente plutôt que la sortie au sommet; cette observation revêt une importance particulière surtout dans le cas d'une tente pourvue d'un tapis de sol. Des expériences ont été effectuées dans le but de déterminer l'effet d'un double toit sur la température moyenne à l'intérieur, d'un toit plus bas et de l'addition d'une cheminée au système de chauffage et d'un tuyau destiné à évacuer les gaz de combustion. La concentration du dioxyde et du monoxyde de carbone et le point de rosée ont été mesurés à divers niveaux à l'intérieur de la tente.

INTRODUCTION

Several parameters of the microclimate of a ten-man arctic tent were examined at CFS Churchill during the month of February 1977. These investigations were carried out in conjunction with an international physiological experiment, Exercise Kool Stool II, organised by the Defence and Civil Institute of Environmental Medicine. In addition to measurements of temperature distributions, humidity, ventilation and toxic gas concentrations, some experiments with the tent liner and with a lowered ceiling were performed in order to assess their effect on interior temperature levels. The effect of adding a chimney to a two-burner camp stove and venting the exhaust directly to the exterior was also examined.

Some earlier work was performed by Pang and Constantine (1) who installed a "heat deflector", or false ceiling at a level of 1.8 m in a ten-man tent heated by three M1950 Mountain stoves. This increased the temperatures at the floor by as much as 10°C, immediately below the deflector by 25°C, and above the deflector by 20°C. A striking feature of the distributions which they obtained was a layer of cold air from the floor level to a height of about 0.3 m.

Observations from arctic exercises have indicated that "tent-eye" and icing of the tent can be serious problems under cold conditions (2, 3). The drying power of the air in a heated tent was questioned by Nolan (4) who found that the components of the mukluk could not be dried in an occupied tent at night when the stoves were extinguished, but instead tended to pick up moisture from the air.

PROCEDURES AND EQUIPMENT

A standard Canadian Forces ten-man arctic tent was used for all experiments. It was pitched in an area which was exposed to the prevailing north-west wind, approximately 15 meters from the nearest building, inside Fort Churchill. As the wind had kept the area relatively free of snow, a bulldozer was used to prepare a platform of compacted snow approximately 0.40 meters thick. The tent was carefully erected to its maximum height, and the fabric was stretched tightly so that the maximum interior volume was obtained. Considerable attention was paid to weather proofing the tent flaps with snow. The wind improved on these efforts during succeeding days and nights by forming a drift around the tent and burying the flaps in wind-packed snow to a depth of at least 0.30 m. On the down-wind side, where the door was located, a drift of packed snow formed against the door to a height of about a meter.

During the daylight hours, the tent was left unoccupied and unheated. It was occupied and heated from dusk to midnight when measurements were being made, and occupied overnight on five occasions by one to three subjects.

The tent was equipped with a liner made of CF-C-584, a vinyon fabric with an air permeability of 180 ml cm^{-2} sec at a pressure differential of 0.0125 m of water.

Temperature Measurements

A rapidly responding iron-constantan thermocouple made of 0.25 mm wires was chosen as the sensing element. A FLUKE digital multimeter, model 8600 A, having an input impedance in excess of 1000 megohms was used to measure the voltages developed by the thermocouple. The reference junction was maintained at 0°C by a snow-water bath in a Dewar flask.

Fourteen temperatures were recorded in each of five vertical planes described by the tent pole and the corners of the tent. Final values were calculated by averaging the temperatures for points with the same vertical and horizontal coordinates. This allowed temperatures throughout the volume of the tent to be condensed into a single cross section, as illustrated by Figure 1 (see Results).

Measurements were taken at night to avoid the influence of solar radiation. One complete series of 70 measurements required about 20 minutes. During this period, temperature drift was negligible.

A ceiling of closely woven nylon was constructed so that it could be suspended across the tent at the upper drying line. The ceiling was employed to note the effect of both tent shape and height on interior temperature distributions.

Heating Equipment

The heat power and physical characteristics of the stoves used in the experiments are given in Table I. Because of the variability of the power of the pressure stoves, some experiments were performed with electrical heat sources. When the electrical and M1950 Mountain stoves were used they were placed 1.0 meter from the centre pole, at 120° angles. The Coleman two-burner stove was placed 0.5 meters from the tent wall next to the door. Another Coleman two-burner stove was fitted with a chimney pipe in order to vent combustion products directly to the outside.

TABLE I

Heater	Mass (empty) (kilograms)	Volume (litres)	Heat Power (kilowatts)	Fuel Volume (liters)	Operation Time(Hours)
Coleman 421-C	4.1	15	3.9	0.85	1.8
Coleman 421-C modified, stack	6.5	20	2.7	0.85	1.8
M1950 Mountain	0.8	2.2	1.5	0.35	1.9
Coleman 621-A	1.8	14	1.0	0.95	7.8
Electrical	-	-	1.33	-	-

Humidity and Toxic Gas Concentrations

The dew point was determined at several levels with an ALNOR Type 7000 Dew Pointer. Air was drawn through a length of transparent plastic tubing into the fog chamber of the apparatus which was heated to maintain a minimum temperature of 15°C. No condensation occurred in the tubing. The pump was operated 150 times before each determination to ensure that the air in the fog chamber and tubing had been changed when sampling locations were changed. Values were checked from time to time with a Drager Multi-Gas Detector, Model 31, which was also used to sample for CO and CO_2 levels.

Ventilation

An ALNOR Velometer Type 3002 was used to measure the inflow of air through a flexible duct. By running a length of this duct under the tent wall and snow flaps to the outside, a positive control over the ventilation rate was achieved.

RESULTS AND DISCUSSION

Temperature Measurements

The temperature increments produced by the electrical heat sources in two types of weather conditions are shown in Figure 1. The "living zone average temperature" (LZAT) is an average of temperatures recorded within a designated living zone. Six values in each plane of measurement were used to determine this average. The points at which these values were obtained were at heights of 15 and 80 centimeters and radial distances of 0, 80 and 160 centimeters from the centre pole. As the occupants of the shelter are most often sitting or lying down when inside, the volume enclosed by these points is representative of the most often occupied areas of the tent.

The isotherms shown on Figure 1 and subsequent figures are in degrees Celcius above ambient. The actual temperature at any point is the sum of the ambient temperature and the temperature shown on the figure at the same location. For example, in Figure 1 with an ambient temperature of -31°C, the actual temperature at any point on the 20°C above ambient isotherm is -11°C. Figures 2 through 5 illustrate typical results obtained in the experiments. Average values of LZAT under various ambient conditions are given in Table II.

There is an obvious difference between the isotherm distribution produced by the electric stoves (Figures 1-3) and that produced by the liquid-fuel pressure stoves (Figures 4 and 5). With the electric heaters, the air in the upper region of the tent is nearly isothermal in contrast to the large temperature gradients typical of a tent heated with a pressure stove. The Coleman lantern, suspended from the centre pole, undoubtedly has an influence on this difference as it was not used when the electrical stoves were employed.

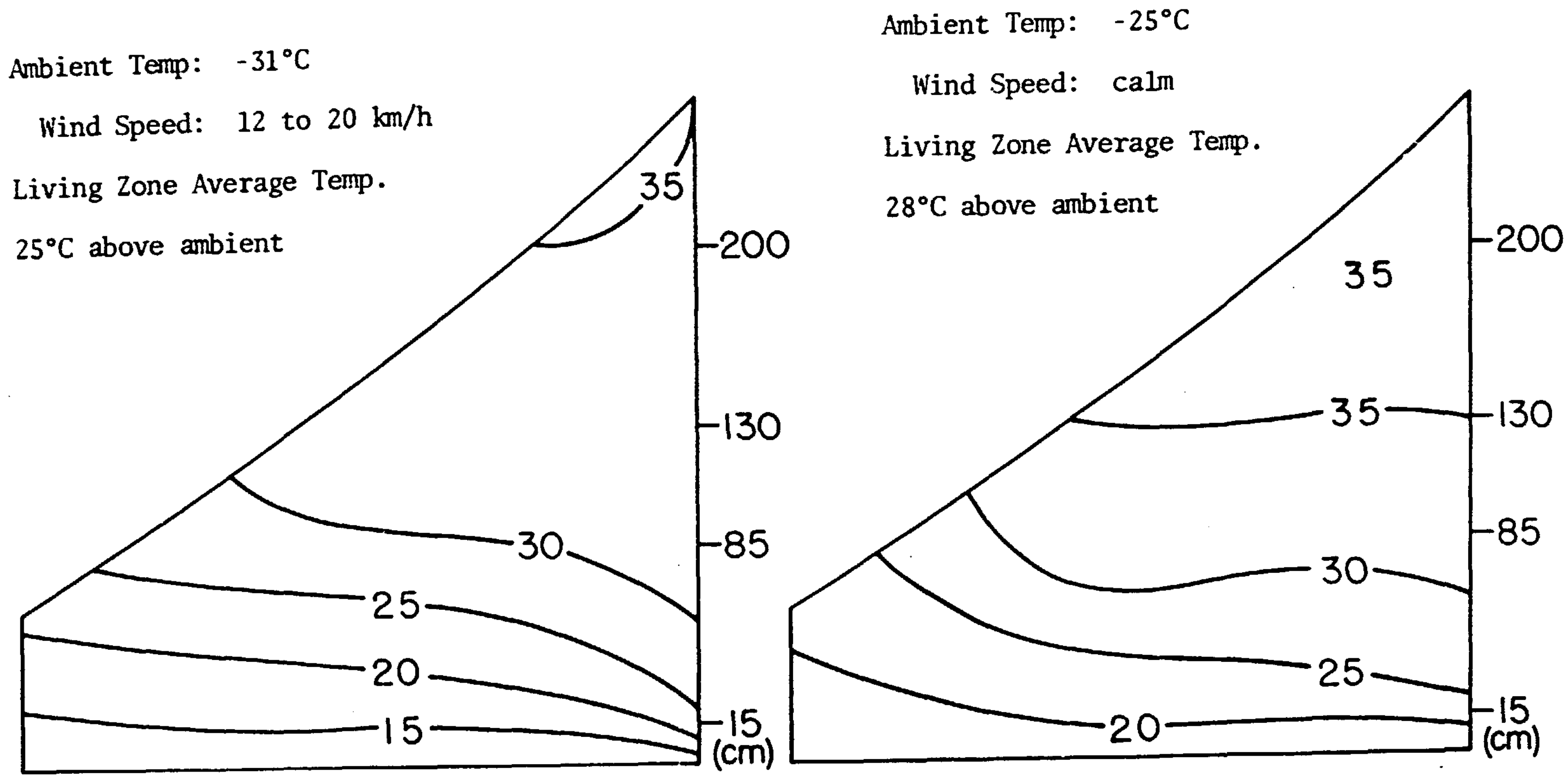

Figure 1. Effect of Wind on Interior Temperature Levels. Note the effect of the wind on the temperatures, especially near the floor. Heating was 4.0 kw electrical. All temperatures are in degrees Celcius above ambient.

TABLE II

Living Zone Average Temperature Increases Above Ambient

Heat Source	Wind	LZAT Increase	Remarks	No. of Trials
Electric	Calm	28°C	vents closed	2
Electric	12 G* 20 km/h	25°C	vents closed	1
Electric	Calm	31°C	vents closed false ceiling	1
Electric	Calm	21°C	vents closed no liner	1
Coleman 421 C and lantern	Calm to light breeze	30°C	2 vents open	2
Coleman 421 C and lantern	Calm	33°C	2 vents open false ceiling	1
Coleman 421 C and lantern	30 km/h	21°C	2 vents open	2
Coleman 421 C and lantern	30 km/h	27°C	2 vents open false ceiling	3
Coleman 421 C and lantern	37 G* 50 km/h	18°C	vents closed chimney	1
2 M1950 Mountain and lantern	12 G* 20 km/h	28°C	2 vents open	1

* Gusting to

The Thermal Resistance of the Tent

Heat loss from a tent involves conduction, convection and radiation mechanisms. An overall thermal resistance can be calculated from equation 1:

$$R = \frac{\sum^{h} S_h T_h + S_{floor} T_{15\ cm}}{Q} \qquad (1)$$

where R is the overall thermal resistance of the tent in $m^2 \cdot C/watt$, S_h is the surface area of the horizontal strip of tent wall between heights

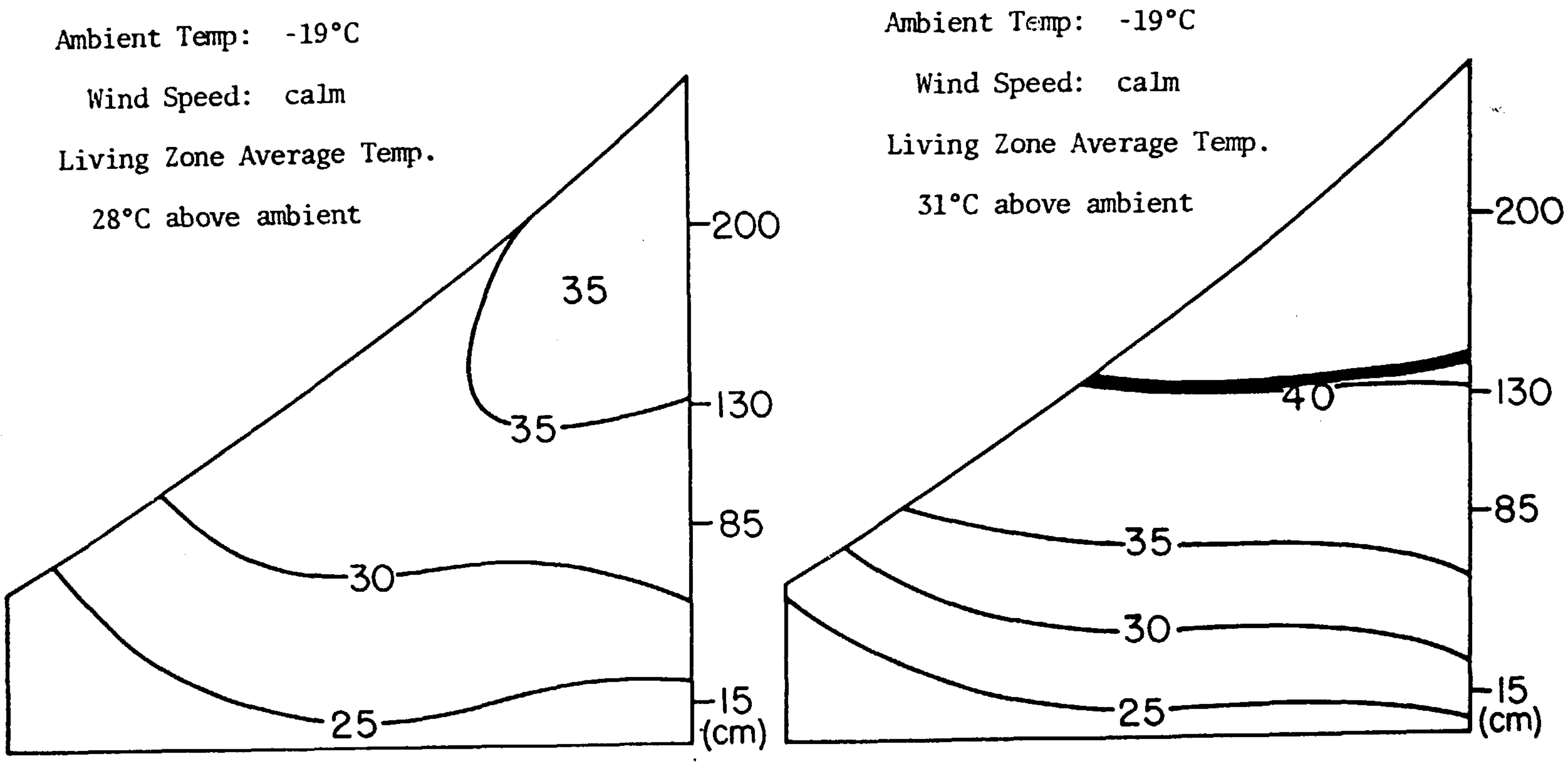

Figure 2. Effect of a Nylon False Ceiling on Interior Temperature levels. The tent on the right has the false ceiling installed (heavy solid line). This addition raised the Living Zone Average Temperature by 3°C. Heating was 4.0 kw electrical. All temperatures are in degrees Celcius above ambient.

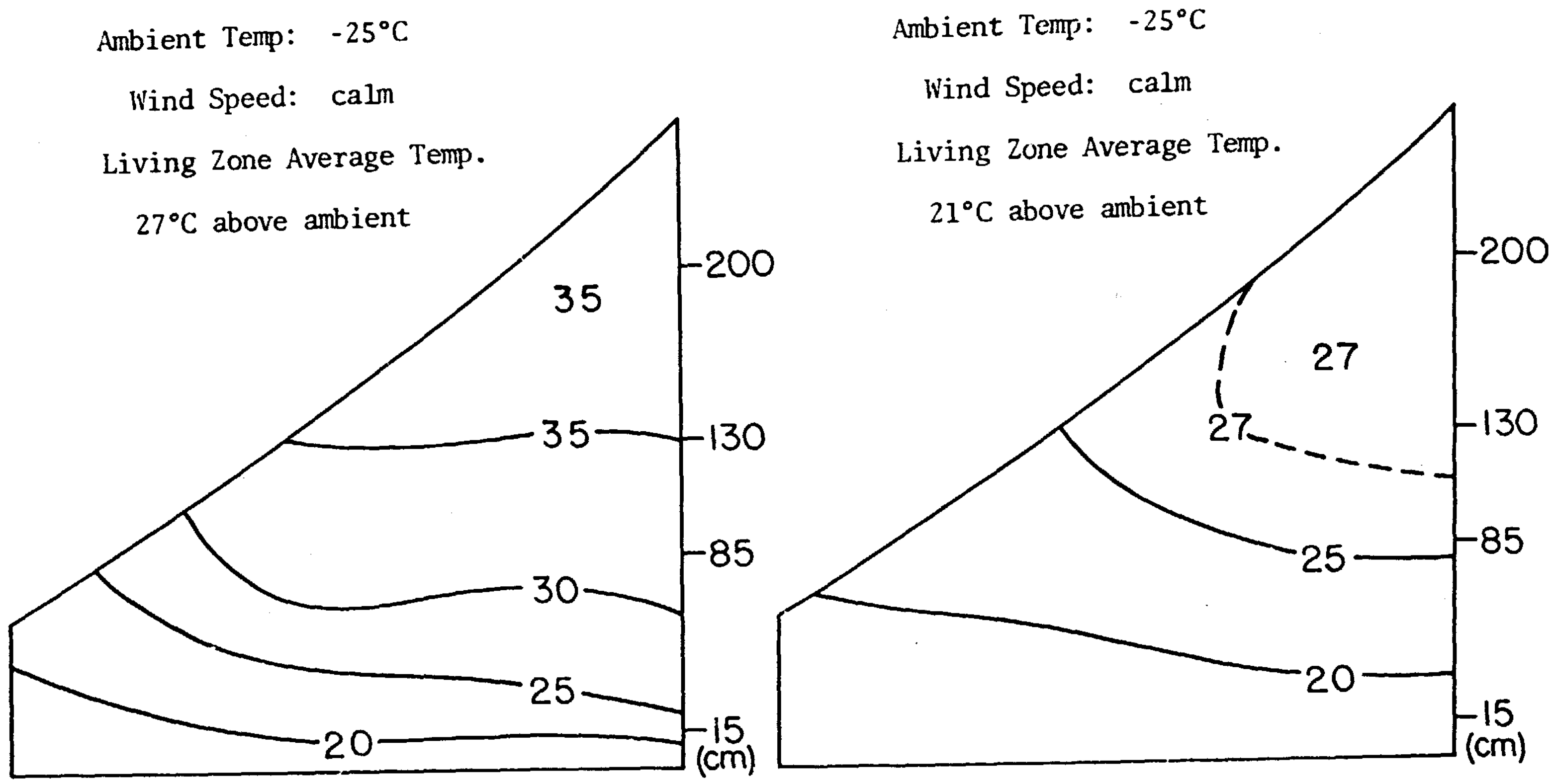

Figure 3. *Effect of the Tent Liner on Interior Temperature Levels. The measurements on the left were performed on the complete tent. The liner was removed and after steady conditions were reached measurements resulting in the diagram on the right were made. Under these conditions it is seen that the liner contributed 6°C to the Living Zone Average Temperature. Heating was 4.0 kw electrical. All temperatures are in degrees Celcius above ambient.*

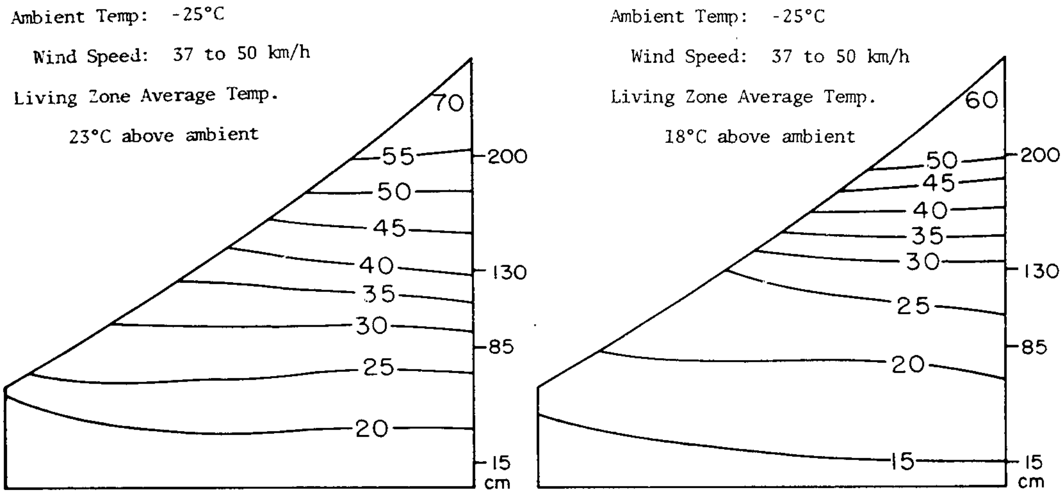

Figure 4. *Effect of a Chimney Pipe on Performance of the Coleman 2-Burner Stove. Measurements were made for the diagram on the left using a unmodified Coleman stove as the heat source. A second stove, which had been fitted with a chimney pipe was used as the heat source for the situation diagrammed on the right. The addition of the chimney pipe resulted in a lowering of the Living Zone Average Temperature by 5°C. In both cases heating was provided by the stove and one lantern. All temperatures are in degrees Celcius above ambient.*

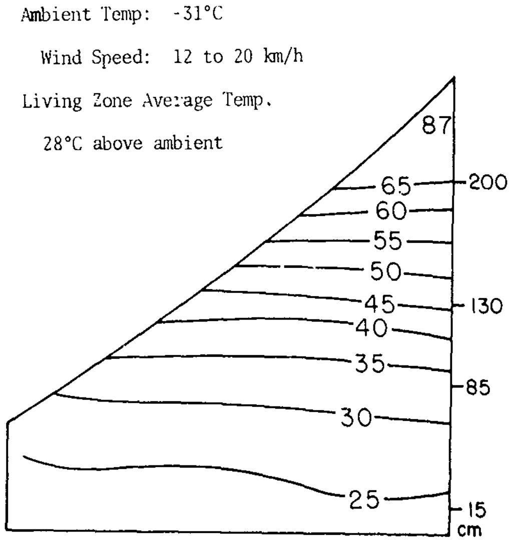

Figure 5. Temperature Distributions Using M1950 Mountain Stoves as Heat Source. Note that the Living Zone Average Temperature is below 0°C while the peak of the tent is extremely hot. The upper region of the tent has a large temperature gradient in contrast to the situations where electrical heating was used without the lantern. Two M1950 stoves and the lantern were used as the heat source. All temperatures are in degrees Celsius above ambient.

h and h-1, S_{floor} is the floor surface area, T_h is the temperature difference between the ambient and the interior air averaged between heights h and h-1, T_{15cm} is the average temperature at 15 centimeters, and was used as an estimate of the floor temperature. Q is the heat power of the three electric stoves (4 kilowatts). The distance between heights h and h-1 was 30 cm in each case, starting from the floor and measuring to the peak of the tent. The thermal resistance of the tent was calculated at 0.31 ± .03 m^2°C/watt. When the liner was removed, the thermal resistance fell to 0.24 ± .03 m^2°C/watt. As in Figure 3, the LZAT was decreased by 6°C. The tent without a liner was uncomfortably cold. In addition to the decrease in air temperature, there was undoubtedly a great reduction in the radiant temperature inside the tent, as the cold wall of the tent was directly exposed. This would increase the heat loss of the occupants by radiation to the cold surfaces of the tent wall. No measurements of radiant temperature were performed.

As shown in Table II, in all cases, wind caused a reduction in LZAT. This is probably due to an increase in ventilation and a decrease in the thermal resistance of the tent walls caused by the moving air. The thermal resistance of the tent walls is due to the existence of a layer of air on the inner and outer surfaces of the fabric. The fabric itself has a thermal resistance of only about 0.02 m^2°C/watt, while each air layer will have a resistance of about 0.1 m^2°C/watt under normal conditions of outdoor calm. At a wind speed of 36 km/h, the thermal resistance of the outer air layer is reduced to about 0.02 m^2°C/watt (6).

Relationship Between Living Zone Average Temperature and Comfort

At thermal equilibrium, the equation for heat flow from the body core to the environment may be written as in equation 2 (5):

$$M = \frac{(T_b - T_a)\,A}{R_b + k\,(R_c + R_a)} \qquad (2)$$

where M is the metabolic rate in watts,
A is the surface area, (1.8 m^2 approximately)
T_b is the body core temperature (37°C)
T_a is the temperature of the environment
R_b is the insulation of the body tissues (0.065 m^2°C/watt)
k is the non-evaporative heat loss fraction (0.7), and
$R_c + R_a$ is the clothing insulation plus the insulation of the ambient air.

While sitting in comfort, M is about 100 watts. Solving for T_a, the temperature at which a man insulated with 0.36 m^2°C/watt would be indefinitely comfortable while sitting is 19°C.

Burton and Edholm (6) exposed subjects to temperatures of -18°C to -12°C for a four-hour period. The subjects were wearing flying clothing which had a thermal resistance of between 0.31 m^2°C/watt and 0.39 m^2°C/watt. Under these conditions, the mean body temperature fell by 2.5°C. Assuming an average body mass of 70 kilograms, the heat loss was an average of 170 Wh. This is the maximum value for the safe loss of body heat (7). Through the exposure, the average metabolic rate was 120 watts. This same average metabolic rate value was obtained by Allen and O'Hara from measurement of soldiers in tents during an arctic winter exercise (8). In order to extend the period of safe exposure from four to six hours, the average temperature gradient from the core to the environment would have to be decreased by one-third, (from 51°C to 34°C). This means the minimum temperature to which a subject wearing clothing having an insulation value in the above range could be exposed without danger of hypothermia for a period of six hours is about 2°C.

Cold-stress discomfort will be felt at a heat debt of 30 Wh, and shivering will begin at a debt of 90 Wh (9). Substituting the heat loss of 125 watts (120 W + 30 Wh/6h) for M in equation 2, assuming a constant metabolic rate of 120 watts, gives 16°C as the minimum temperature for comfort over a six-hour period. Using M=135 watts (120 W + 90 Wh/6h) in equation 2 gives a minimum temperature of 14°C as the temperature at which shivering will be prevented over a period of six hours.

Cold-stress will result in a reduction in circulatory heat input to the extremities in an effort to conserve heat. In tents in cold weather, the temperature of the feet will be a particularly important factor in the comfort of the occupants. Little heat is generated by the feet, so the reduction in circulation will mean that the feet will cool to near the temperature of their immediate environment which is the coldest part of the heated tent. A foot temperature of 16°C or 17°C is reported as extremely cold while 6°C or 7°C is reported as painful (10).

Two M1950 Mountain stoves and a lantern are capable of maintaining a minimum temperature of 2°C in the living zone of the tent when the outside temperature is above -36°C. In the case of the two-burner Coleman stove, the outside temperature must be above -23°C. It is commonly observed that soldiers tend to heat their tents to the point at which the snow floor melts in an effort to be comfortable. From Figures 4 and 5, it can be seen that if the LZAT is in excess of 10°C the snow floor will probably be melting, while a LZAT of 16°C is required for comfort with the present clothing if the parka is not worn.

Effect of a False Ceiling

Adding a false ceiling in windy conditions produces a higher LZAT than is the case when the ceiling is used in calm conditions. The observation that temperatures increase both above and below the ceiling indicates that the ceiling is probably reducing the ventilation rate of the tent. The ceiling increases the LZAT by 3°C in calm conditions when ventilation rates are low. In windy weather, it produces an increase of 6°C when higher ventilation rates would be expected without the ceiling. The even larger effect obtained by Pang and Constantine (1) is probably explained by higher initial ventilation rates combined with the more effective seal produced by their smaller deflector. In their case, the smaller deflector placed at a higher level in the tent would be more effective in restricting air flow between the deflector and the liner.

Ventilation

An upper limit of the ventilation rate was determined in a well weather-proofed tent. The vents at the peak were closed and the electric heat was turned on. The initial ambient temperature was -20°C and the wind speed was 20 km/h. After a steady state had been reached, the top vents were opened and an attempt was made to measure the change in the temperature distribution in the tent produced by the ventilation. No changes were found. A duct was then opened at floor level and an air inflow rate of 5 liters/sec was measured. This flow produced an easily measured temperature change. The flow was probably, therefore, at least equal to and perhaps greater than the normal rate of ventilation in a tent which is well weather-proofed with snow. No attempt was made to determine how small an inflow would produce a measureable temperature change.

Toxic Gas Concentrations

In all of the experiments with the unmodified pressure stoves carbon monoxide levels were low, the averages being less than 5 ppm. Carbon dioxide likewise did not reach toxic levels, being below 5000 ppm.

The addition of a chimney pipe to the Coleman stove was therefore an unwarranted modification. The standard equipment did not tend to create a toxic environment in these tents. It should be noted that cooking pots were not placed on the naphtha stoves during the measurements. It is likely, therefore, that the Coleman two-burner and the M1950 stoves burn efficiently in a tent in cold weather and significant amounts of toxic gases are only formed as a result of flame quenching during cooking (10, 11).

Figure 4 shows that the addition of a chimney pipe to the Coleman stove produced a large decrease in the LZAT. Since a significant portion of the heat of combustion is lost up the stack and at the same time standard equipment appears to burn quite efficiently, it is felt that stoves with chimneys are not necessary. A new heater that burns at least as efficiently as current ones and is designed to minimize flame quenching while cooking is required.

Humidity

A limited survey of dew points in a tent heated by a Coleman 421-C and lantern (500 cp) was undertaken. Although not conclusive, the results were felt to be sufficiently interesting to include in this report.

Figure 6 shows the distribution of dew points obtained. Under the given conditions, the air in the tent was extremely dry. The relative humidity was less than 25% in the region above the lower drying line. The average dew point by inspection is about -3°C. In addition to the stove and lantern which provided water vapour at a rate of approximately 600 g/h, two occupants provided approximately 80 g/h (12). With a ventilation rate of 5 liters/sec, the average dew point should have been about 19°C. Obviously processes such as diffusion through the walls, regain of the cotton fabric, and condensation on the walls and floor effectively dehumidified the air. A tent with ten occupants and the same heat and light sources would have a vapour input of approximately 1 kg/h. If the dehumidification processes are constant, the average dewpoint under these conditions would be about 2°C. A steaming pot and a few steaming mugs, plus clothing drying on the drying lines could easily raise the dew point to 5°C. In this case the region of the tent below the 35°C isotherm in Figure 5 would be a condensing region. In these conditions, condensation should occur to a level somewhat above this on the liner as the wall is cooler than the adjacent air. Consequently, drying of clothing should not be attempted at any level much below the condensation level of the inner wall.

When the stoves are extinguished at night, the rate of vapour addition from ten occupants will still be about 400 g/h. The ventilation

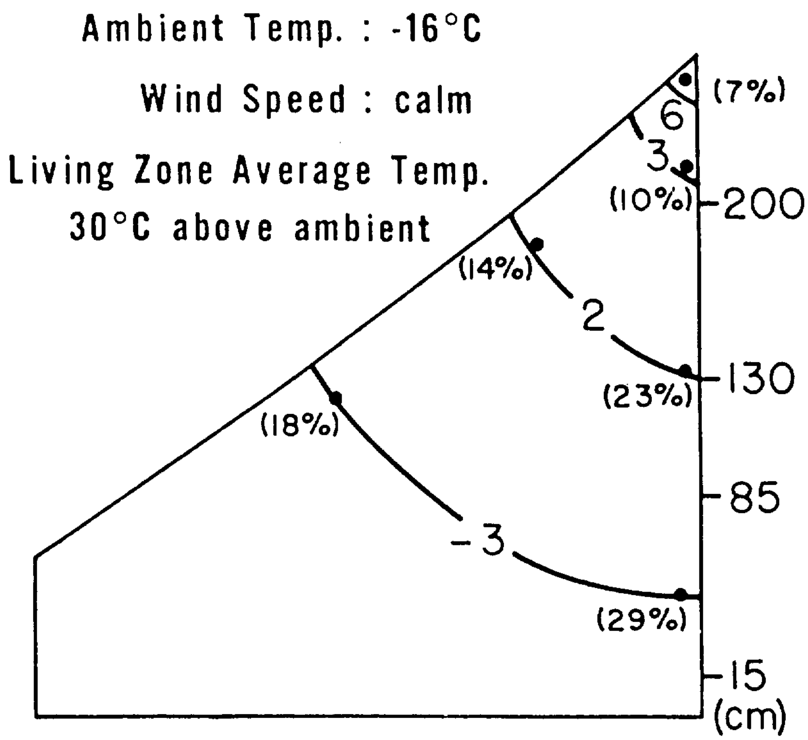

Figure 6. Dew points in °C are indicated on the isopleths. The relative humidity is given at the sampling points. Heat sources were a Coleman two-burner stove and lantern. Temperature distribution within the tent is similar to that shown in Figure 4.

rate will be reduced by virtue of the colder interior temperatures. In all probability condensation will occur throughout the tent and drying of clothing will not occur.

CONCLUSIONS

1. There is a large temperature gradient in a tent when the standard stoves and lantern are used for heating and lighting.

2. The lowered ceiling increased the average temperature in the living zone of the tent by 3°C. Temperatures at the sleeping level increased only very slightly.

3. As negligible amounts of toxic gases are produced when the stoves are being used for space heating only, the addition of a chimney pipe is not required. During cooking, toxic gases are produced because of flame quenching. It is felt that preventing the production of toxic gases is preferable to venting them with a chimney pipe, as a considerable loss of heat is involved in the latter case.

4. The ventilation rate of a well weather-proofed ten-man tent was found to be less than 5 litres/sec. The controlling factor was found to be the restriction on the inflow of cold air at low levels, not the restriction on flow out at the peak. This point should be particularly important in tents with integral floors. Some provision for a minimum inflow of cold air is required to assure good ventilation.

5. With the current issue of standard clothing, minus the parka, a minimum average temperature of +2°C is required in the living zone to prevent gross discomfort or dangerous heat loss of the occupants, while a temperature of 16°C is necessary for comfort. This latter requirement results in the melting of snow floors.

6. When night temperatures are below -26°C, more heat than can be provided by a Coleman two-burner stove and lantern or two M1950 stoves in conjunction with a lantern is required to maintain a minimum living zone average temperature of +2°C.

7. Drying of clothing should not be attempted at a level below the condensation level on the tent liner, or in an occupied and unheated tent as the clothing will not dry and may even pick up moisture.

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