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THE CALCULATION OF HEAT LOSS FROM TENTS

by

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UNITED STATES ARMY
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The purpose of this project was to improve the habitability of tents. As a first step, a method was developed for calculating the heat loss from tents. Basically, it is the same as the method used by heating engineers for estimating the heat loss from buildings but modified for tents. The principal difference is the conductances or constants by which the various areas are multiplied to determine the heat loss through that area. These were evaluated by making calculations for tents for which heat loss data was available. A step-by-step procedure and a list of recommended conductances is given. The use of this method for improving comfort is discussed.

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PREFACE

There is a need to design tents that are as comfortable as possible with the greatest ease of transportation and erection. The experimental evaluation of alternative designs is time-consuming and expensive, so as much as possible should be done with calculations that require no experiment. Since temperature is the first consideration in comfort, a method of calculating the heat loss from tents was developed.

Appreciation is expressed to Dr. Constantin J. Monego and Dr. Leslie A. McClaine for their helpful discussions in the course of this work.

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THE CALCULATION OF HEAT LOSS FROM TENTS

Introduction

The heating requirements of buildings have been routinely calculated by engineers for years. The methods are empirical, based on some laboratory tests and on the results of measurements on actual buildings. The equations and constants may be found in manuals and textbooks.[1,2]

We have available a certain amount of heat loss data from measurements made some years ago at this Command on tentage still listed as standard. The methods used for buildings will be used to calculate the heat loss from some of these tents for comparison with measured data, initially using constants for buildings obtained from the manuals. The constants may then be adjusted in order to make the calculations agree with the data. In this way a method and list of constants applicable to tents may be developed. Finally, the method will be tested by performing calculations for types of tents not included in the above process but for which data is available. This process will then be used to rank various design options with respect to their effectiveness in preventing heat loss.

Preliminary Discussion

There are two principal paths of heat loss from a structure: conduction through the walls; and infiltration, or warm air leaking out and cold air leaking in.

Heat conduction in the classical sense refers to the flow of heat between surfaces of a solid object as a function of the temperature difference between those surfaces. However, in tents the temperature difference of the air inside and outside and "conduction through the walls" must include radiation and convection inside and outside and in any air spaces within the wall as well as classical conduction in any solid part of the wall. The "conductances" we will use have no direct relationship with a thermal conductivity and are simply quantities by which the wall area and temperature difference of the air may be multiplied to obtain the heat flow. Thus:

$$Q_C = h_t A \Delta T \qquad (1)$$

where h_t is the total conductance of the wall or other surface (roof, floor), A is the area and ΔT the difference between inside and outside air temperatures. The total conductance may be obtained by combining the inside surface conductance, h_i, the outside

[1] J. R. Allen, J. H. Walker, and J. W. James; Heating and Air conditioning; McGraw Hill, 1946

[2] ASHRAE Guide and Data Book: Fundamentals and Equipment for 1965 and 1966

surface conductance, h_o, and the wall conductance, h_c. For buildings, the wall conductance may be obtained from the thermal conductivities and dimensions of the various materials used. Both conductivities and conductances are extensively tabulated for a variety of wall constructions and construction materials. For tents, the conductance of some fabrics may be available; in some cases, such as insulated walls, they may be calculated from known conductivities and, if necessary, they may in some cases be estimated with enough accuracy. For buildings, the surface conductances have been determined by test and are tabulated for different kinds of surfaces and as a function of wind speeds. For tents, the surface conductances will be the principal constants that we will vary to obtain a match with the data, though we will start with values selected from those tabulated for buildings. Since the conductances considered are in series, their reciprocals are additive. Thus for the total conductance:

$$h_t = \frac{1}{\frac{1}{h_i} + \frac{1}{h_c} + \frac{1}{h_o}} \qquad (2)$$

In buildings infiltration, the second pathway for heat loss, principally occurs through the crack in window joints. In manuals the volume of leakage per length of joint is tabulated for a variety of window descriptions and as a function of wind speed. The values tabulated were determined by experiment. With tents we may be able to make some use of these values by assuming that the space around the bottom of an unbanked tent is similar to the leakiest window listed. Also with tents we must consider leakage directly through the fabric.

If a heating engineer does not have the data to use the crack method or does not feel it is justified, he may use the volume change method of estimating infiltration. In this approach he estimates from a general knowledge of the nature of the room construction how many times in a given period the entire volume of air in the room will change. For example, it has been determined that an inside room with no windows will have at least one-half volume change per hour. A drafty location such as a warehouse will have about three changes per hour with other rooms ranging in between these extremes. With tents we may use this method, adjusting the values upward in line with the leakier nature of tents.

Having determined the volume leakage we may calculate the heat loss from infiltration.

$$Q_A = \rho\, C_p\, V_a\, \Delta T \qquad (3)$$

where ρ is the density and C_p the specific heat of air averaged over the range of normal temperatures. If we use the volume change method we will have

$$V_a = NV \qquad (4)$$

where N is the number of times in a period the entire volume of air changes and V is the inclosed volume.

We wish to establish the heat loss characteristics of a tent independent of the weather at a particular time. Since both Q_C and Q_A are being treated as linear functions of ΔT (though they probably are not because h, ρ and C_p probably all depend on temperature) we can divide by ΔT to get the per-degree heat loss.

$$L = \frac{Q_A + \sum_n (Q_C)_n}{\Delta T} = \rho\, C_p\, V_a + \sum_n (h_t A)_n \tag{5}$$

where n refers to the various tent surfaces that must be treated separately.

Evaluation of Parameters

In a 1962 report by Monego and Rasor,[3] and in an earlier report by Sanders,[4] there are considerable data on the heat loss from the General Purpose Medium Tent. Much of these data were taken to compare various experimental liners but this work also included considerable control data taken with no liner. It is this latter information that was used to get a first evaluation of the constants.

Weather conditions other than the temperature, particularly the wind and clouds, affect the heat loss from a tent. So even though the data are correlated in terms of heat loss per degree, a considerable variation can be expected. Therefore, we shall assume certain conditions and calculate what we would expect as maximum and minimum heat loss values for comparison with the largest and smallest measured values. Maximum heat loss conditions are assumed to be night-time clear skies with a moderate wind (the wind velocity will be discussed later). With clear skies there will be radiational cooling and the surface of the tent might be colder than the outside air. However, we will assume for our calculation that the surface is the same temperature as the outside air so that h_o is infinite and $1/h_o = 0$. For infiltration we will assume that the space around the bottom of the tent leaks the same as the worst situation reported for a window at the same wind velocity. (In the tests reported in references 3 and 4 the tents were not banked or sealed in any way around the bottom.) We will also estimate the leakage directly through the canvas and consider this as a part of the total infiltration.

[3] C. J. Monego and H. J. Rasor; Heat Retention Properties of Tent Liners, Textile Series Report No. 122; US Army Quartermaster Research and Engineering Center, Natick, MA; AD 292050; 1962

[4] J. L. Sanders; A field Test of Heat Requirements for General Purpose Tents; Technical Report T-21, FEA 55097-F, Quartermaster Field Evaluation Agency, Fort Lee, VA; 1957

Minimum heat loss conditions are considered to be represented by cloudy skies and no wind. With no wind we may assume negligible infiltration. Also, with no wind there will be only natural convection outside the tent and with cloudy skies there will be little radiational cooling; therefore we may use the same surface conductance outside as we use inside.

In any tent the floor must be treated as a special case. This is particularly true when the floor is the ground as in the reported tests. Since we do not want to become involved in soil conductivity we must estimate the temperature of the ground and use just the surface conductance. If in winter a tent has been heated for even a short time, the ground will start to thaw, so the logical temperature to assume for the ground is 0°C. We do recognize, however, the existence of a large vertical temperature gradient in such a floorless tent. Consequently, the temperature difference causing heat to flow out through the floor area is much less than the difference between the average air temperature and 0°C. We shall estimate a temperature in the lower part of the tent and use this figure to calculate the ground heat loss. This contribution to total heat loss will be the same in both the maximum and minimum calculations.

Before proceeding, we should say something about units. The tents are manufactured to dimensions given in round numbers in feet. In some cases these numbers appear in the official name of a tent. The handbook values used in the calculations are given as rounded-out approximations in English units. The results of the tests referred to are also in English units. Therefore, it seems best to make the calculations in English, occasionally converting to SI and of course giving the results in both English and SI units.

The General Purpose Medium Tent is 16 x 32 feet (4.88 x 9.75 m). There is a 5-½-foot sidewall, 10 feet at the peak, and a hipped roof, making it only 17 feet long at the ridge; so the floor area is 512 square feet, the wall area is 536 square feet (allowing for a height increase to 6 feet at the doors), and the roof area is 640 square feet.

Because of the high vertical temperature gradient recognized in these tents, the average temperature difference from the air in the lower part of the tent to the ground at 32°F was assumed to be 10°F, even though the average temperature difference reported from inside to outside air in the General Purpose Medium Tent tests was 41°F. The surface conductance for a rough surface with no wind is given in reference 2 as 2.0 Btu/hr ft²°F. So the loss to the ground for both the maximum and minimum calculation is:

$$L_g = \frac{h_g A_g \Delta T_g}{\Delta T} = 250 \text{ Btu/hr}^\circ\text{F} \quad (6)$$

The conductance of the 9.85-ounce duck tent fabric is 6.70 Btu/hr ft²°F. (This and some other values could not be determined exactly but were estimated from reference 5 and similar sources.) The surface conductance of a reasonably smooth surface with no wind is given in reference 2 as 1.5 Btu/hr ft^2°F. Using this value for both inside and outside surfaces for the minimum heat loss calculation we get:

$$h_t = \frac{1}{\frac{1}{1.5} + \frac{1}{6.7} + \frac{1}{1.5}} = 0.674 \text{ Btu/hr ft}^2 \text{ °F} \quad (7)$$

Applying this to calculation of the rate of heat loss through both the walls and roof we get:

$$L_{w,r} = 0.674 \times (536 + 640) = 793 \text{ Btu/hr °F} \quad (8)$$

Since there is no infiltration in the minimum heat loss condition, we have:

$$L_{min} = L_g + L_{w,r} = 1042 \text{ Btu/hr °F} \quad (9)$$

Most heat loss calculations for buildings are made at 15 mph so we will use this wind condition for our maximum calculations. The air penetration of the duck at this velocity was estimated to be 6 ft^3/ft^{2}hr. We will apply it to half the tent area. The largest leakage tabulated in reference 2 for any window at 15 mph is 176 ft^3/ft hr. The perimeter of the tent is 96 feet. Therefore:

$$V_a = \frac{6 \times 1176}{2} + 176 \times 96 = 20{,}424 \text{ ft}^3\text{/hr} \quad (10)$$

$$\rho\, C_p = 0.0749 \text{ lb/ft}^3 \times 0.240 \text{ Btu/lb°F} \quad (11)$$

$$= 0.0181 \text{ Btu/ft}^3 \text{ °F}$$

and

$$L_A = \rho\, C_p V_a = 369.5 \text{ Btu/hr°F} \quad (12)$$

for our maximum heat loss calculation.

For maximum conditions we will have, recalling our assumption that h_o is infinite and thus $1/h_o$ is zero:

[5] P. Wing and C. J. Monego; A Comparison of the Cenco-Fitch and Guarded Hot Plate Methods by Measuring Thermal Insulation; Textile Engineering Laboratory Report No. 184, US Army Quartermaster Research and Development Command, Natick, MA; 1957

$$h_t = \frac{1}{\frac{1}{1.5} + \frac{1}{6.7}} = 1.226 \text{ Btu/hr ft}^2 \text{ °F} \tag{13}$$

$$L_{w,r} = 1.226 \times 1176 = 1441.8 \text{ Btu/hr ft}^2 \text{ °F} \tag{14}$$

and

$$L_{max} = L_g + L_A + L_{w,r} = 249.8 + 369.5 + 1441.8 = 2061 \text{ Btu/hr°F} \tag{15}$$

This maximum calculated value of 2061 must be compared with the largest measured value of 1452 in either references 3 or 4. The minimum calculated value of 1042 must be compared with the smallest measured value of 861.

We see that both calculated values are too high when compared to measurement. An examination of the calculations show us that the single constant that most affects the results is the surface conductance. For the minimum condition calculation with no appreciable infiltration this was most true. So we shall use the minimum calculation to adjust our value of surface conductance.

The same number, 1.5 Btu/hr ft² °F, was used to apply to the walls and the roof both inside and outside the tent. This number was obtained from manuals as applicable to the inside surfaces of building walls and also to the outside surfaces with no wind. So we have no reason not to use it for the vertical inside wall of a tent or the outside wall with no wind or radiation to the sky. Also, the sloping roof does not seem to be enough different on the outside to justify the use of a different number. However, the hot air trapped in the peak of the roof does seem to make conditions quite different on the inside of the roof. The principal mechanism of so-called "surface conductance" is convection. The poor circulation in the peak will limit convection so we are justified in applying a lower surface conductance to the inside roof area of the tent. (That the higher average temperature in the peak will not appreciably affect the calculations is explained in Appendix B.) We shall calculate what this value should be to make the calculated heat loss for minimum conditions match the smallest measured heat loss.

So

$$L_{min} = 861 = L_g + L_{w,r} = 250 + L_{w,r} \tag{16}$$

and therefore

$$L_{w,r\ min} = 611 \tag{17}$$

Applying equation (7) just to the vertical walls we calculate

$$L_w = 0.674 \times 536 = 361 \text{ Btu/hr}^\circ\text{F} \quad (18)$$

and therefore

$$L_r = L_{w,r} - L_w = 611 - 361 = 250 \text{ Btu/hr}^\circ\text{F} \quad (19)$$

thus

$$h_{t\ r} = \frac{L_r}{A_r} = \frac{250}{640} = 0.3906 \text{ Btu/hr ft}^2\ ^\circ\text{F} \quad (20)$$

Solving equation (2) for h_i

$$h_{i\ r} = \frac{1}{\frac{1}{h_t} - \frac{1}{h_c} - \frac{1}{h_o}} = \frac{1}{\frac{1}{0.3906} - \frac{1}{6.7} - \frac{1}{1.5}} = 0.573 \text{ Btu/hr}^\circ\text{F} \quad (21)$$

We next calculate L_{max} using this value for the inside surface conductance of the roof area:

$$h_{t\ r\text{-}max} = \frac{1}{\frac{1}{0.573} + \frac{1}{6.7}} = 0.528 \quad (22)$$

$$L_{w,r\text{-}max} = 0.528 \times 640 + 1.226 \times 536 = 995 \quad (23)$$

$$L_{max} = 250 + 370 + 995 = 1615 \text{ Btu/hr}^\circ\text{F} \quad (24)$$

This is seen to be still larger than the largest measured value of 1452. However, it was calculated assuming a wind velocity of 15 mph. This would mean that the wind speed averaged over the entire night would have this value. However, in checking the test data it was determined that there was not this much wind in the location of the tests. Assuming the ground, wall, and roof losses as calculated above to be correct, the infiltration loss would have to be 207 instead of 370 to give the measured value of 1452 Btu/hr°F. If this loss is proportioned to the wind velocity, this would require a wind of

$$\frac{207}{370} \times 15 = 8.4 \text{ mph} \quad (25)$$

This compares reasonably well with the winds actually recorded.

To test the assumptions and method of calculation derived above, the process was applied to another size tent. In a 1964 report by Chaloux,[6] there is considerable data on the Tent, General Purpose, Small. This is a six-sided pyramidal tent, made of the same 9.85-ounce duck as the General Purpose Medium and also has no floor. It is 8.67 feet (2.64 m) on a side, 5 feet (1.52 m) at the eaves and 10.5 feet (3.20 m) at the peak. The floor area is 195.3 square feet, the roof area 242.0 square feet and the sidewall area is 260.1 square feet. We shall use the numbers determined for the GP Medium tent, above, and calculate for the GP Small. The average ΔT observed in the tests was 38°F.

$$L_g = h_g A_g \frac{\Delta T_g}{\Delta T} = 2.0 \times 195.3 \times 10/38 \quad (26)$$

$$= 102.8 \text{ Btu/hr°F}$$

$$L_{min} = L_g + L_{w\ min} + L_{r\ min} = L_g + .674 \times 260.1 + 0.3906 \times 242.0 = 373 \text{ Btu/hr°F} \quad (27)$$

For infiltration we shall use an 8.4 mph wind velocity rather than 15 mph so the penetration through the walls is 6 x 8.4 $ft^3/15\ ft^2 hr$ which will be applied to half the wall and roof area and the crack penetration is 176 x 8.4/15 which is multiplied by the perimeter.

$$\text{So: } V_a = \frac{6 \times 8.4}{15} \times \frac{242 + 260}{2} + \frac{176 \times 8.4}{15} \times 52 = 5968 \text{ ft}^3 \quad (28)$$

and

$$L_A = \rho C_p V_a = 0.0181 \times 5968 = 108 \text{ Btu/hr°F} \quad (29)$$

$$L_{max} = L_g + L_A + L_{w\ max} + L_{r\ max}$$

$$= 102.8 + 108 + 1.226 \times 260.1 + .528 \times 242 \quad (30)$$

$$= 657 \text{ Btu/hr°F}$$

These calculated values of 657 and 373 compare with Chaloux's (reference 6) largest and smallest measured values of 647 and 468. The agreement is good but the excellent agreement on the high side makes us wish it were better on the low. However, although there were 25 determinations from which the largest and smallest values were taken, an analysis of the data distribution indicates that there might not have been enough measurements to insure that the extremes of weather condition were included. This analysis

[6] P. N. Chaloux; Heat Retention Test on Tent Liners; AMXRE-MED – 896; Mechanical Engineering Division, US Army Natick Laboratories; 1964

indicated that there was probably a wider range of weather conditions during the GP Medium tests so that it is well that we chose them for determining the values of the constants.

Method of Calculating for an Untested Shelter

The above calculations were made by matching data taken under particular conditions. For some studies of habitability a similar approach of calculating maximum and minimum heat losses may be best. On the other hand, heat loss values averaged over a season may be more useful for some purposes such as estimating fuel consumption. A method of calculating the average heat loss for a season will be given below, but it could easily be modified to give maximum and minimum values.

For either purpose it seems practical to use a volume change method for infiltration rather than the crack method tried above. Such figures are usually taken as average values for the season. Calculations on the GP Medium data (see Appendix A) indicate that appropriate values of volume change for tents would be on the high side of those given for buildings. Thus a fairly tight tent would have about two changes per hour, an unbanked tent like the GP tents in the tests would be about three per hour and under the worst conditions we might assume up to five per hour.

To get average heat loss values for the wall and roof we propose to calculate average total conductance values based on averaging the total conductance values for the extreme conditions as derived in the maximum and minimum calculations earlier. For the ground loss for a floorless tent we must approximate an average test temperature. For this we shall assume that there is about one-fifth the temperature difference causing heat to flow out such a floor as for the rest of the tent and divide the appropriate conductance by five. Other floors will be treated more like a wall. Conductance values not specifically treated will have to be estimated as are some in Table 1.

A suggested step-by-step procedure to follow in calculating the average heat loss from a tent follows:

(1) Calculate all areas and volume of tent.

(2) Select appropriate conductances either from Table 1, by estimation or possibly by calculation.

(3) Calculate an average, all-weather conductance for each area from the equation

$$h_{t\text{-}av} = \tfrac{1}{2}\,(h_{t\text{-}max} + h_{t\text{-}min})$$

$$= \tfrac{1}{2}\left(\frac{1}{\frac{1}{h_i} + \frac{1}{h_c} + \frac{1}{h_o}} + \frac{1}{\frac{1}{h_i} + \frac{1}{h_c}}\right) \qquad (31)$$

TABLE 1

Conductances

Inside Surface	Btu/hr ft^2 °F	Watts/m^2 °C
Vertical walls	1.5	8.5
Sloping roof	.57	3.2
Roof of an A tent	1.0	5.7
Roof of cylindrical tent	1.0	5.7
Ground, no floor	.4	2.3
Insulated floor	1.15	6.5
Wooden floor	1.0	5.7
Outside Surface		
Cloudy, no wind	1.5	8.5
Clear and windy	∞	∞
Insulated floor on snow	∞	∞
Wooden floor	1.5	8.5
Material		
Heavy canvas	6.7	38
Canvas with standard liner	2.4	13.6
Fiberglass, one inch	.26	1.5
Wooden floor	.26	1.5

where for the corresponding condition:

h_i is the inside surface conductance,

h_c is the conductance through material,

h_o *is the outside surface* conductance.

(4) Estimate the air volume changes, N

(5) Calculate heat loss

$$L = L_A + L_C$$

$$L = \rho \; C_p \; N \; V + \sum_n \left(h_{t\text{-}av} A \right)_n \qquad (32)$$

where n refers to each area that must be treated separately and

$$\rho \; C_p = 0.0181 \text{ Btu/ft}^3 \text{ °F} = 1212 \text{ j/m}^3 \text{ °C} \qquad (33)$$

In modifying this to calculate separate maximum and minimum heat loss values, the separation of terms in step 3 is obvious. In step 4 it is suggested that the value of N *selected for the shelter in question* be increased by one for a maximum value and decreased by one for a minimum.

Example of Calculation

Tent, Frame-type, Insulated, Sectional, 16′ x 16′.

This is the Jamesway tent. There is some data on heat loss from a double version, 16′ x 32′, of this tent in Sanders, reference 4.

This tent is semi-cylindrical with one-inch fiberglass insulation and a plywood box floor.

$$A_r = \frac{16\pi}{2} \times 32 = 804.2 \text{ ft}^2 = 74.72 \text{ m}^2 \qquad (34)$$

$$A_w = \pi 8^2 = 201.1 \text{ ft}^2 = 18.68 \text{ m}^2 \qquad (35)$$

$$A_g = 16 \times 32 = 512 \text{ ft}^2 = 47.57 \text{ m}^2 \qquad (36)$$

$$V = \frac{\pi 8^2}{2} \times 32 = 3217 \text{ ft}^3 = 91.10 \text{ m}^3 \qquad (37)$$

$$h_{t\text{-}av\ w} = \tfrac{1}{2}\left(\frac{1}{\frac{1}{1.5}+\frac{1}{.26}+\frac{1}{1.5}}+\frac{1}{\frac{1}{1.5}+\frac{1}{.26}}\right)$$

$$= 0.207 \text{ Btu/ft}^2\ {}^\circ\text{F} = 1.19 \text{ watts/m}^2\ {}^\circ\text{C} \tag{38}$$

$$h_{t\text{-}av\ r} = \tfrac{1}{2}\left(\frac{1}{\frac{1}{1.0}+\frac{1}{.26}+\frac{1}{1.5}}+\frac{1}{\frac{1}{1.0}+\frac{1}{.26}}\right)$$

$$= 0.194 \text{ Btu/hr ft}^2\ {}^\circ\text{F} = 1.11 \text{ watts/m}^2\ {}^\circ\text{C} \tag{39}$$

$$h_{t\text{-}av\ g} = \frac{1}{\frac{1}{1.0}+\frac{1}{.26}+\frac{1}{1.5}} = .181 \text{ Btu/hr ft}^2\ {}^\circ\text{F} = 1.04 \text{ watt/m}^2\ {}^\circ\text{C} \tag{40}$$

This is a fairly tight shelter so we shall assume two volume changes per hour.

Using equation (32)

$$L = 0.01809 \times 2 \times 3217 + 0.207 \times 201.1 + 0.194 \times 804.2 + 0.181 \times 512$$

$$= 407 \text{ Btu/hr}^\circ\text{F} = 216 \text{ watt/}^\circ\text{C} \tag{41}$$

The losses reported by Sanders, reference 4, were 450, 440, 420, 340, 290, averaging 388 Btu/hr°F. This is reasonable agreement.

Relation of Heat Loss to Habitability

The primary objective of this work was a study of the factors affecting habitability of shelters rather than the question of fuel consumption. Heat loss was chosen as the most tangible of these factors and certainly an important one. However, since the heat loss can be overcome by increasing the heat input, for comfort or habitability, it may be more important to consider how the heat is lost.

As a beginning, we shall repeat the calculations on the GP Medium tent, keeping the different heat loss paths separate, calculate ways that the losses may be reduced, and finally consider how they affect the comfort of the occupants.

Using equations (31) and (32) and the values from Table 1, we have:

$$L = L_{(air)} + L_{(floor)} + L_{(wall)} + L_{(roof)},$$

$$= \rho\, C_pNV + A_f(h_t)_f + A_w(h_t)_w + A_r(h_t)_r \tag{42}$$

Estimating N to be 3 we have:

$$L = 206 + 205 + 509 + 292 = 1212 \text{ Btu/hr}^\circ\text{F}$$

Obviously the greatest heat loss is through the walls and the effect of reducing any other loss is limited. For example, if we could reduce the infiltration by half by carefully banking the tent and lacing all the seams tight we would only reduce the loss by 8% from 1212 to 1109 Btu/hr°F. On the other hand, if the tent were carelessly set up on uneven ground so the volume changes averaged 5 per hour, the loss would only increase 11% to 1349 Btu/hr°F. However, it seems obvious that the drafty tent would be much more uncomfortable than the tight one.

Another example would be to consider the tent erected over a wooden platform. This would only reduce the heat loss by 9% to 1100 Btu/hr°F but would reduce the temperature gradient in the living volume to a much more comfortable value than normally observed in a tent.

A simple suspended liner allows free air exchange under it so has little effect on the surface conductance and we can only consider the increased material. Thus, if we calculate for the standard liner we only reduce the loss by 12% from 1212 to 1072 Btu/hr°F, but again we may have a greater effect on the comfort because the liner is usually a lighter color than the canvas and so will reduce the radiation exchange between the bodies of the occupants and the surface.

If we do all the above –– banking, platform and standard liner –– we would have a loss of 857 Btu/hr°F. This would be an improvement of only 30%, but the increase in comfort would be appreciable. A platform would not be convenient in the field, but a simpler ground covering such as a double layer of tarpaulin of the same weight as the tent should also improve the temperature gradient. This would have about the same loss as the bare ground so a tent with this on the ground and banked, and with a standard liner would have 80% of the heat loss of a regular GP Medium tent but be considerably more comfortable.

Finally, let us consider whether anything can be done about our largest heat loss, that through the walls. Without considering whether it is logistically reasonable we can conceive of an efficient liner, one containing an inch of fiberglass insulation, for instance. Such a liner applied just to the vertical walls would reduce this loss from 509 to 111 Btu/hr°F. This is large enough to improve the comfort by allowing a given stove to operate at a lower heat output and so at a lower temperature, and so improve the lateral distribution of temperature.

So a GP Medium tent with this insulating liner, well banked to confine the infiltration to two volume changes per hour and with a double tarpaulin floor, would have a heat loss of 745 Btu/hr°F or about 60% of that of a regular tent. We cannot assign a numerical value to the improvement in comfort but it would be considerable.

Conclusion

With the equations and numerical constants described here, the heat loss from any tent or shelter may be estimated with reasonable accuracy. In some cases where the construction or materials differ widely from those considered here, a certain amount of imagination may be necessary in assigning values to the constants but this should be possible and still allow the results to be reasonable estimates. This procedure should be particularly useful in determining the relative merits of proposed modifications to existing shelters.

For most of this report, only the overall heat loss was considered. In terms of fuel economy and survival under adverse conditions this is, of course, of the first importance. In terms of comfort it may not go far enough. A modification that materially increases the comfort but with only a slight effect on the heat loss might be worthwhile. Several of these are suggested in the last section.

The method of calculation given in this report should assist in the development of more comfortable shelters. This document reports research undertaken at the US Army Natick Research and Development Command and has been assigned No. NATICK/TR-79/017 in the series of reports approved for publication.

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APPENDICES

APPENDIX A

Volume Change Values

What volume change figures would give the same results as those obtained with the crack methods for the GP Medium tent? $V = 3788\ ft^3$. In our first calculation for 15 mph we get in equation (10), $V_a = 20{,}424\ ft^3/hr$.

So

$$N = \frac{V_a}{V} = 5.4 \text{ changes/hour} \tag{44}$$

But this was thought to be too high a wind velocity. A value for the lower velocity of equation (25) would be

$$N = 5.4 \times 8.4/15 = 3.0 \text{ changes/hour} \tag{45}$$

For the GP Small from equation (28) $V_a = 5968\ ft^3/hr$ and since $V = 1335\ ft^3$, $N = 4.5$ per hour. This was for 8.4 mph wind velocity.

These figures indicate that the order of magnitude of the volume change of air in tents is 2 to 5 changes per hour.

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APPENDIX B

TEMPERATURE GRADIENT CONSIDERATIONS

The total conductance calculated for each surface is to be multiplied by the difference between the average inside temperature and the outside temperature to get the heat flow through that surface. The fact that the air trapped near a surface may be at a considerably higher temperature will not affect this procedure since the trapped air is considered as part of the surface in the inside surface conductance term. If we tried to include the effect of this high temperature in some way, it could only be to effectively increase the wall conductance. With a low surface conductance, an increase in the wall conductance has little effect on the total conductance. When one term becomes dominant, such as the surface conductance here or the wall conductance of an insulated wall, it might be better to ignore the other terms, but just when to do this is not obvious.

It is inconsistent with the above to estimate the effect of the vertical temperature gradient on the floor heat loss as was done in calculating the GP Medium data. This was caused by the different approaches used in the two cases. However, the final method of calculation presented is consistent in that reduced conductance rather than a reduced temperature difference is used for a bare-ground floor.

LIST OF SYMBOLS

Q_C	Heat loss by conduction	Btu/hr	watts
Q_A	Heat loss by infiltration	Btu/hr	watts
ΔT	Difference between average indoor and outdoor temperature	°F	°C
L_C	$Q_C/\Delta T$	Btu/hr°F	watt/°C
L_A	$Q_A/\Delta T$	Btu/hr°F	watt/°C
L	*Total heat loss per degree* $(L_C + L_A)$	Btu/hr°F	watt/°C
h_t	Total Conductance	Btu/hr ft² °F	watt/m² °C
h_i	Inside surface conductance	Btu/hr ft² °F	watt/m² °C
h_o	Outside surface conductance	Btu/hr ft² °F	watt/m² °C
h_c	Conductance through wall	Btu/hr ft² °F	watt/m² °C
A	Area	ft²	m²
V	Volume	ft³	m³
V_a	Volume of air changed per unit time	ft³/hr	m³/sec
N	Number of volume changes	1/hr	1/sec
$\rho\ C_p$	Density x specific heat of air	Btu/ft³ °F	j/m³ °C