*Chapter 16*

# Body Heat as a Strategy for Winter Survival in Housepits

*Richard MacDonald*

## Introduction

Heating strategies in pithouses during the very coldest times of the year would likely be focused on the element of basic survival rather than one of comfort. As was suggested by Hayden et al. (1996), some pithouse dwellers may have employed a strategy of using body heat at relatively high occupant densities as the principle heating method. While there are few historical references to the heating or insulating properties of pithouses, one such account documented by Reverend J.B. Good during the mid-1800s, describes a pithouse in the Lytton area during a very cold winter day that was crowded with people to a point where the temperature became uncomfortably warm:

> These underground dwellings for winter occupation were delightful places to enter on days when the wind was blowing fiercely from the north, sending the thermometer at times to twenty below zero provided only three or four families held possession of them. . . . But during what we may term our revivals, when we used to crowd these places or dens with hearers thick as bees in a hive, then the heat would grow insufferable. (Good as cited by Kennedy and Bouchard 1987:261)

In a similar account from the same period, artist Paul Kane related his observations of a housepit at Walla Walla in the winter:

> . . . twelve or fifteen persons burrow through the winter, having little or no occasion for fuel; their food of dried salmon being most frequently eaten uncooked, and the place being excessively warm from the numbers congregated together in so small and confined a space. They frequently obliged, by the drifting billows of sand, to close the aperture, when the heat and stench become unsupportable to all but those accustomed to it. (Kane as cited by Rice 1985:99)

A question arises from these accounts which warrants investigation. Would body heat, under optimum circumstances, be enough alone to keep a pithouse temperature at a minimum to ensure occupant survival? If so, does structure size affect the suitability of this strategy?

To test the hypothesis of this heating strategy, a model of heat generation from occupant body heat versus heat loss through the building envelope has been developed for three sample housepits (HP's 90, 12, and 7), each located at Keatley Creek in the Lillooet area. This hypothesis is being tested under the following constraints:

1) The use of fire was limited to food preparation only and not as a heating source. (If a fire had been used as a heating source, a smoke hole in the roof would be required as well as a lower opening to provide fresh air for occupant survival. This influx of cold air would likely negate any heating benefits of the fire.)
2) The occupants of the test housepits were poor and had only the most basic of clothing and blankets. (Willow or sagebrush bark robes and leggings, fish skin moccasins and sage bark or dog skin blankets as discussed by Hayden 1990:90–91.)

# Methodology

The sample housepits for this study were chosen for several reasons. They represent a satisfactory cross section in the range of sizes from very small (HP 90), small (HP 12), to large (HP 7). More importantly, these housepits have been among the most thoroughly studied of those at the Keatley Creek site.

Simplified versions of these structures (see Figs. 1–3) were evaluated using current building design analysis methods described in mechanical engineering handbooks (Stein and Reynolds 1992; Ashrae 1989). From this, occupant heat gain and heat loss through the various components of each housepit was calculated. Given that some materials which were used in pithouse construction are not represented by present day building materials, comparable materials were selected that most closely represent the thermal properties of prehistoric building materials.

The following issues will be considered in each of the following sections:

1) Climatic Data
2) Occupant Heat Gain
3) Population Ranges for Study Housepits
4) Total Heat Gain From People
5) Area and Volume Calculations for Study Housepits
6) Heat Loss Calculations

## Climatic Data

Given the close proximity of Keatley Creek to the Lillooet weather reporting station, the temperature values given (Appendix I) can be considered very accurate for the site conditions at the present time. The assumption was made that these values would be relevant to the Keatley Creek area at the time of occupation.

A value of -25°C (Appendix I.1) is listed as the outdoor design temperature for the Lillooet area and will be used for this study. Included in Appendix I.1 is a brief definition of the outdoor design temperature.

The external design temperature of the ground, which is essentially the earth temperature next to a structure below grade, takes into account a time lag for the soil at a given depth to become colder as the adjacent outside air temperature cools (refer to definition in Appendix I.3). A temperature difference of 15.6°C from the mean January air temperature (Appendix I.3) was derived from tables and will be used in the below grade heat loss calculations (Appendix VI).

While there are no precise data available for winter indoor temperatures, there is evidence that early hunters lived at temperatures below what we consider adequate, and possibly did so with some degree of comfort (Hayden 1990:89–102). Historical observations record minimally clothed natives in Terra del Fuego as surviving temperatures as low as 2°C for long periods (Cena and Clark 1981:16). An indoor temperature range from 5°C to 10°C was selected for use in the calculations as determined in Appendix I.4.

## Occupant Heat Gain

Three different methods were used to calculate the heat gain from a typical occupant in watts per person. Two contemporary building design methods were examined using comparable activities with consistent results. A third method was used to account for the unusual variables associated with this non-standard building type. From this, an occupant heat gain in the range of 90W to 107W per person (Appendix II) was derived.

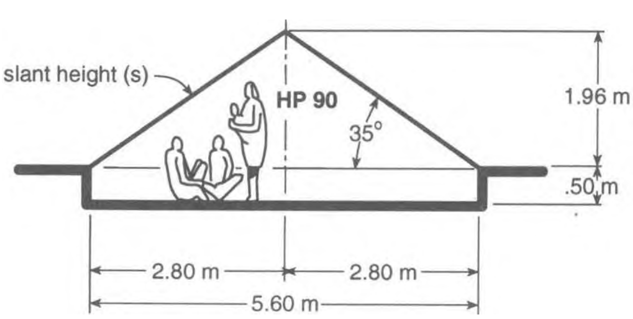


**Figure 1. Simplified Sectional Diagram of Housepit 90.**

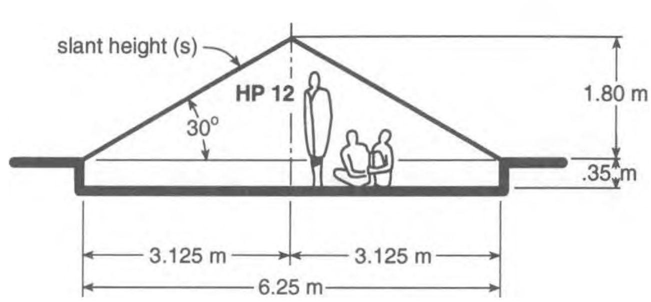


**Figure 2. Simplified Sectional Diagram of Housepit 12.**

## Population Ranges for Study Housepits

The populations for each housepit have been determined by two different methods. The first method assigns a fixed density to each housepit (Hayden et al. 1996) which relates to their floor areas. The population estimates derived from these fixed densities are listed in Appendix III.1.

In order to better compare the body heating strategy in different sized housepits, a range of densities have been applied to both the smallest and largest housepits. This method is important to develop a model of how body heating of the inside of a housepit is affected by both the density of people and by the size of the house. The population estimates from the range of densities are listed in Appendix III.2. Other estimates by Alexander (Vol. II, Chap. 2) indicate that even the highest density estimates used in this study may be too conservative.

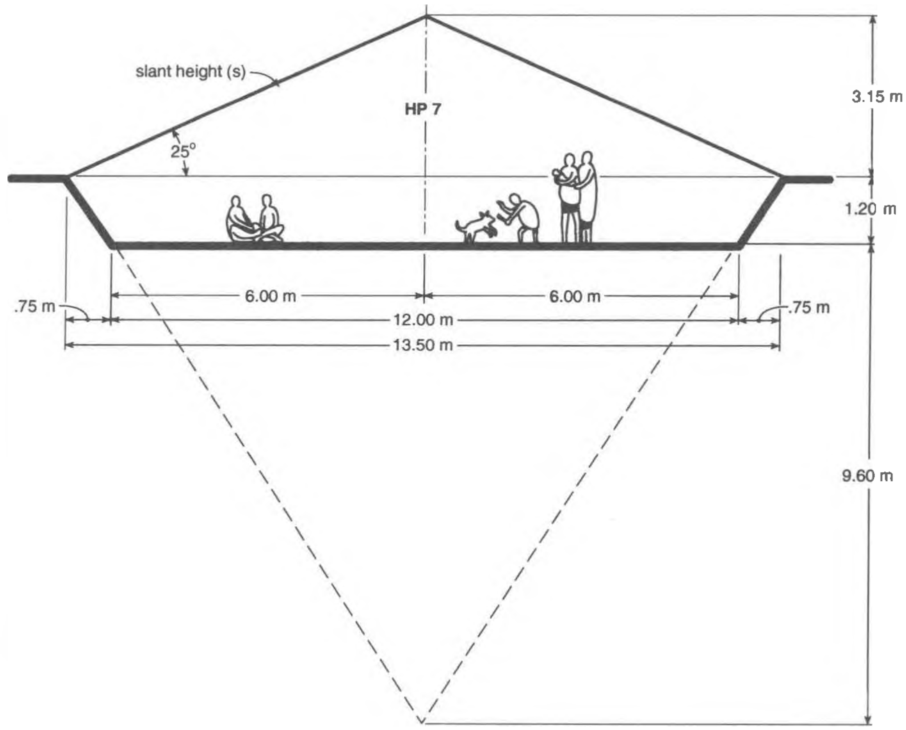


**Figure 3. Simplified Sectional Diagram of Housepit 7.**

## Total Heat Gain from People

The occupant heat gain has been multiplied by the population of each housepit to get a range of total heat gain in watts. This procedure has been applied to the three methods for determining housepit populations as discussed in the previous section. The occupant heat gain derived from population estimates at fixed densities are listed in Appendix IV.1. Occupant heat gain derived from population estimates through a range of densities are listed in Appendix IV.2. Appendix IV.3 lists the occupant heat gain from actual population range estimates.

## Area and Volume Calculations for Study Housepits

While it is possible to accurately determine the floor areas of the study housepits from the remaining ground depressions, the volumes are less certain. There is little evidence remaining to determine the roof pitch. Given this, however, there are a number of roof slope requirements which are useful in determining a range of probable roof pitches. A minimum roof pitch of 20° was chosen to maintain adequate headroom, limit rainwater penetration and provide sufficient underpinning for the roof beams (Vol. II, Chap. 15). In order to prevent earth cover from washing off of the roof, and to provide a low grade for easy access through the smoke hole by the occupants, the maximum pitch chosen was 35°. In each case it was assumed that the pitches would be as low as is practically possible to lessen the structure volume to be heated.

For the smallest of the study housepits, HP 90, a pitch of 35° was assumed in order to provide sufficient headroom space and because the entrance was from the side rather than via the smoke hole. For HP 12, which is slightly larger, a roof pitch of 30° was assumed adequate for headroom requirements. An average roof pitch of 25° was assumed for the largest structure, HP 7, which is located on a hillside and would likely incorporate both maximum and minimum pitches. The area of each housepit floor, wall, and roof, together with the total volume of the structure has been calculated (Appendix V) for use in the heat loss section.

## Heat Loss Calculations

Heat loss through the floors and walls and into the ground has been calculated for each housepit (Appendix VI) and added together to get a total below grade heat loss in watts. The heat loss through the roof has been derived from the summation of the thermal resistance values of each component of the roof construction. The reciprocal of this value (or thermal transmittance value) is applied to each housepit roof that, when factored with the roof areas and temperature differences, yield a heat loss range in watts. Although a snow cover would increase the overall insulating efficiency of the roof assembly, it has not been factored in the calculations. The purpose of this study is to consider occupant survival during the coldest conditions.

Given both the need by the occupants of some fresh air, and the potential for leaks through both the structures themselves and their openings, some warm air would certainly leave the structure and be replaced by cold air. This process is called infiltration and accounts for a portion of the overall heat loss. A range of this heat loss has been calculated (Appendix VI) based on a range of number of air changes each hour. The volume of each housepit is multiplied by the number of air changes per hour and the temperature difference to give a heat loss range in watts.

The total heat loss for each structure is the sum of all of the above heat loss values. The total heat loss for HP 90 has been calculated to fall within the range of 1104W and 1495W (Appendix VI.1.f). For HP 12, the total heat loss ranges from 1204W to 1600W (Appendix VI.2.f). The largest structure, HP 7, has a heat loss range from 6478W to 9982W (Appendix VI.3.f). A simplified diagram (Fig. 4) has been included to clarify and relate the different calculations used to quantify the transfer of heat from an occupant to the housepit and the transfer of heat from the housepit to the exterior environment.

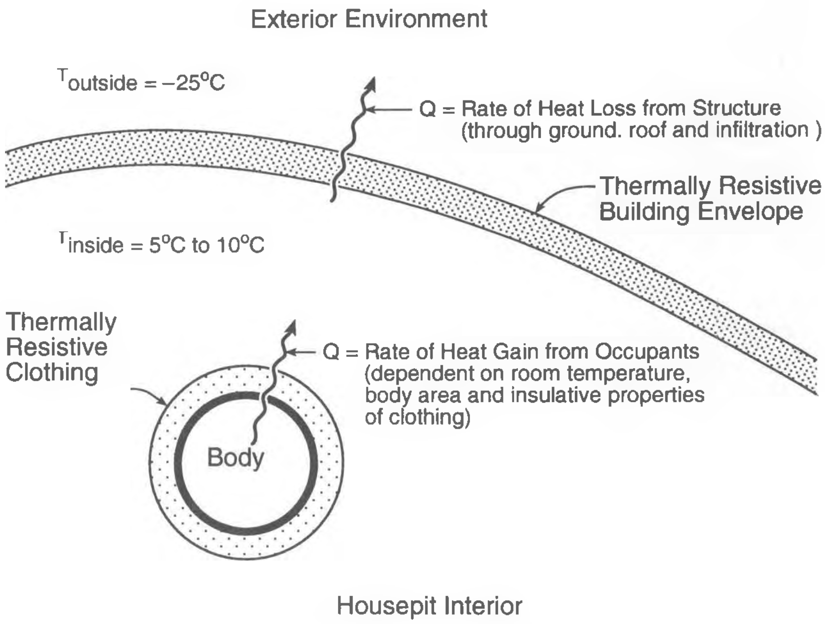


**Figure 4. Diagram of Heat Gain Process.**

# Analysis

The summary of heat loss values (Appendix VI.4) indicates the effects that the size and shape of housepits have on the heat losses from the different components. The heat losses from the walls, floors and roofs of the two smaller housepits (HP 90 and HP 12) vary greatly from those of the larger housepit (HP 7). This can be explained using a simplified model. The area of a circle when doubled in size, increases by the square, or four times. This is roughly the magnitude of difference between the smaller and larger housepits (refer to heat loss range, Appendix VI.4.a).

The smallest housepits would likely have employed the assumed maximum roof pitch to gain headroom within the structure (refer to Figs. 1–3). The result of this would be a greater proportional roof area on the smaller housepits as compared to the larger one. With this larger proportional roof area comes an increase in roof component percentage heat loss (refer to percent average of total heat loss, Appendix VI.4.b).

While heat loss from the walls, floor and roof are governed mainly by area, the infiltration heat losses relate directly to volume. These heat loss values vary substantially between the large housepit and the smaller ones. Again in simple terms, when the size of a cone is doubled, the volume increases by the cube, or eight times the volume. This is roughly the magnitude of difference found with the large and smaller housepits (refer to heat loss range, Appendix VI.4.a). Moreover, the number of heat sources (bodies) increases only as a function of floor area and not volume.

Given that the assumptions made on housepit sizes, shapes, materials and construction are correct, then the heat loss for any given structure is static. Heat gain (assuming occupant body heat only), on the other hand, is not. Occupant populations are difficult to determine and generally change to some degree over time. This can have a major effect on heat generation. The population estimates derived from fixed densities (Appendix III.1) may be generally accurate, but do not allow for easy comparisons of the effects of housepit size at a given occupant density or occupant density at a given housepit size. By employing a wide range of densities (Appendix III.2) for a given housepit, the required population for effectively heating the structure through body heat can be examined.

By comparing the total heat loss values (Appendix VI.4.a) with the occupant heat gain values derived from ethnographic population estimates of housepits with fixed densities (Appendix IV.1), it can be seen that there is a very close balance between heat loss and heat gain in the smaller housepits. The larger housepit, however, does not have enough heat generated to even begin to offset the heat losses. For this heat balance to be achieved in HP 7, the occupant density would have to be increased to about one person for each 1.5 $m^2$ (Appendices IV.2 and IV.4.a) from the 2.5 $m^2$ deemed adequate for smaller structures. In simple terms this would mean a population of HP 7 of about 75 rather than 45. While densities of one person per 2.0 $m^2$ are recorded with some frequency for ethnographic housepits, densities of 1.5 $m^2$ per person are probably at the absolute limit and may only occur with the smallest structures in the coldest climates (Hayden et al. 1996), although Alexander's density estimates approach this value (Vol. II, Chap. 2).

# Conclusions

Given all assumptions, it would appear from the near exact balance of the heat loss and heat gain in the smaller housepits that the assumed indoor design temperatures could be easily maintained by body heat alone for the outdoor design temperature of -25°C. Even with the steeper roof pitch as discussed earlier, the accompanying increased roof heat loss would not be sufficient to negate this heating strategy. If the smallest housepit had a very deep floor and a lower pitch roof, the indoor temperatures could be much higher.

As explained in the analysis section above, HP 7 does not even begin to come close to being able to be heated by body heat alone. A state of equilibrium between heat loss and heat gain could exist, but only at an indoor temperature of approximately 0°C. At this temperature survival would be unlikely over a longer period.

Another factor working against the body heat strategy in the largest housepits is the process of heat stratification. With the large volume and the high upper ceiling void that is created in large housepits, body heat would migrate upwards into this ceiling void where it would be of less use in creating a warmer environment. The warmer air being located next to a part of the roof with the least earth cover would be lost to the exterior environment at a much high rate. Inherently, as with any structure of this size, the laws of physics prevent this heating strategy from working unless the occupant population could be dramatically increased.

The above analysis and conclusions are based on a number of assumptions, some of which could be more accurately defined through further research, and others which will remain difficult to determine reliably. Given this situation, the research conducted here seems to suggest that heating some pithouses, particularly those in the smaller size range, at Keatley Creek using body heat alone, would likely have been viable. Thus other methods of heat generation or heat conservation were probably used in the larger structures, involving supplementary costs.

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# Appendix I — Climatic Data (Lillooet Area)

**1) Outdoor Design Temperatures [National Building Code of Canada, Supplement 1990]**

The winter outdoor design temperature listed below represents the lowest temperature at the weather recording station (Lillooet) below which only a small percentage of the hourly outside air temperatures in January occur. The 1.0% value depicts a frequency level of hours that temperatures have been equalled or exceeded by 99% of the total hours in the months of December, January, and February.

January 1.0% = *-25°C*

**2) Mean January Temperatures [Environment Canada Statistics]**

day mean temperature = -2°C
night mean temp. = -9°C
overall mean temp. = *-5.6°C*

**3) External Design Temperature of the Ground [Ashrae 1989:25.6]**

Heat transfer through walls and floors to the ground depends on the difference between the room air temperature and the ground temperature outside as well as the wall and floor materials and the conductivity of the surrounding earth. Thermal inertia causes a time lag between outside air temperature changes and corresponding changes in ground temperature. This results in a variation in ground temperature at different depths. The ground surface temperature fluctuates about a mean value by a specific amplitude, which varies with geographic location. External design temperatures of the ground can be determined by subtracting the amplitude value from the mean winter air temperature. The amplitude for the Lillooet area has been determined by referring to the map of Lines of Constant Amplitude [Ashrae 1989:25.6 figure: 4].

from map of lines of constant amplitude (A)
= 10°C

mean January air temp. ($t_a$)
= -5.6°C

design temp. difference
= $t_a - A$ = -5.6°C – 10°C = *15.6°C*

**4) Indoor Design Temperature = 5°C to 10°C**

While no data exist for room temperatures in the Keatley Creek pithouses at the time of occupation, it has been assumed that room temperatures colder than 2°C would make survival unlikely. Heat given off from the occupant's bodies along with some ground heat would likely have regulated winter indoor temperatures well above the minimum for bare survival. A minimum room temperature range from 5°C to 10°C has therefore been assumed.

# Appendix II — Occupant Heat Gain (body heat as only heat source)

Heat flow from the body of a person into the immediate environment can be slowed using insulation (clothing and blankets). With an increase in body height or, more specifically, in surface area, comes a corresponding increase in heat loss. Another factor affecting the rate of heat flow from a body is the temperature of the immediate environment (room temperature). This heat loss from the body acts as a source of heat gain for the environment and is often an important factor used in building design. While there are several methods for calculating this heat gain for building design (as shown below), each assumes an environmental temperature of approximately 20°C (normal room temperature) and the user wearing certain clothing (light shirt and slacks).

**1) Occupant Heat Gain — method: 1 [Ashrae 1989:26.7, table: 3]**

using comparable activity of "seated, very light work" sensible heat per person (adjusted to account for normal proportion of men women, and children) = 70W/person

**2) Occupant Heat Gain — method: 2 [Stein and Reynolds 1992, table: 5.8]**

using comparable activity of "office"
area per person = 9.29 $m^2$/person
sensible heat gain = 7.88W/$m^2$
9.29 $m^2$/person × 7.88W/$m^2$ = 73W/person

The heat gain values derived from methods 1 and 2 may be useful to begin to look at the rough impact of heating a pithouse with body heat, but another method which accounts for other variables could be employed. The lower environmental temperature, different body sizes, higher consumption of caloric rich food and greater use of clothing could be factored using the basic formula to determine heat flow as described in the following section.

**3) Occupant Heat Gain — method: 3**

$$[Q = U \times A(T_b - T_r)]$$

where:

$Q$ = rate of heat flow
$U$ = reciprocal of thermal resistance values
$A$ = surface area of human body
$T_b$ = body temperature (37°C)
$T_r$ = room temperature (5 – 10°C) [Appendix I.4]

It should be noted that this formula does not allow for the many variables of body heat loss such as losses due to evaporation of body moisture, latent respiration, radiation and skin diffusion, all of which are covered in detail by Fanger (1970:19–37). Certain assumptions have been made regarding clothing and average body surface area.

Clothing used by the poorer families that lived in the Keatley Creek pithouses included willow bark and sagebrush bark robes and leggings, moss filled ponchos, fish skin moccasins, and blankets of sagebrush bark (Teit 1906:218). It appears that only the richest families had high quality fur and animal skin blankets and clothing. Insulative or thermal resistance values (clo-values) for clothing used have been interpolated from comparables compiled by Fanger (1970:33) along with standard surface air film values as follows:

surface air film = $.030\text{m}^2{}^\circ\text{C/W}$
bedding (1 clo assumed) = $.155\text{m}^2{}^\circ\text{C/W}$
(1 clo = $.155\text{m}^2{}^\circ\text{C/W}$)
airspace = $.050\text{m}^2{}^\circ\text{C/W}$
clothing (1 clo assumed) = $.155\text{m}^2{}^\circ\text{C/W}$
total R-value = $.390\text{m}^2{}^\circ\text{C/W}$
U-value = 1/R-value = *$2.564W/m^2{}^\circ C$*

The average body surface area has been determined by Jennings (1978) at roughly 1.9 $m^2$ for a man and 1.6 $m^2$ for a woman. A value .85 $m^2$ for children was assumed to be a reasonable approximation. Since there is no information available on the ratios of men, women and children for the study pithouses at the time of occupation, the following proportions have been assumed:

25% men (at 1.9 $m^2$)
25% women (at 1.6 $m^2$)
50% children (at .85 $m^2$)
average body surface area =
$.25(1.9\ m^2) + .25(1.6\ m^2) + .5(.85\ m^2) = 1.30\ m^2$

If people slept tightly together the effective surface area for any given body would be reduced, thereby reducing body heat loss. This condition has not been assumed for this study.

**Occupant Heat Gain**

$$Q = U \times A(T_b - T_r)$$

*lower range:*

$Q = (2.564\text{W/m}^2{}^\circ\text{C})\ (1.30\ \text{m}^2)\ (37^\circ\text{C} - 10^\circ\text{C})$
$= 89.99\text{W}$

*upper range:*

$Q = (2.564\text{W/m}^2{}^\circ\text{C})\ (1.30\ \text{m}^2)\ (37^\circ\text{C} - 5^\circ\text{C})$
$= 106.66\text{W}$

*range: 90W to 107W/person*

# Appendix III — Population Ranges for Study Housepits

**1) Population Estimates from Fixed Densities**

Housepit population estimates as a function of floor area have been explored and determined to be roughly 2 $m^2$/person for small housepits and 2.5 $m^2$/person for large housepits (Hayden et al. 1996, Spafford 1991). By using these density values the resident populations of each study housepit can be determined as follows:

HP 90 (area from 5.1.1 = 24.6 $m^2$) × 2.0 $m^2$/person = 12 people

HP 12 (area from 5.2.1 = 30.7 $m^2$) × 2.0 $m^2$/person = 15 people

HP 7 (area from 5.3.1 = 113.1 $m^2$) × 2.5 $m^2$/person = 45 people

**2) Population Estimates from a Range of Densities**

In order that the body heating strategy can be compared for all housepits at a fixed resident density or conversely for several densities at a fixed housepit size, population estimates as a function of floor area have been determined through a range of densities (1.0 $m^2$/person to 4.0 $m^2$/person) for the smallest and largest housepit as follows:

*HP 90 (24.6 $m^2$)*

(at 1.0 $m^2$/person) = 25 people
(at 1.5 $m^2$/person) = 16 people
(at 2.0 $m^2$/person) = 12 people
(at 2.5 $m^2$/person) = 10 people
(at 3.0 $m^2$/person) = 8 people
(at 3.5 $m^2$/person) = 7 people
(at 4.0 $m^2$/person) = 6 people

*HP 7 (113.1 $m^2$)*

(at 1.0 $m^2$/person) = 113 people
(at 1.5 $m^2$/person) = 75 people
(at 2.0 $m^2$/person) = 57 people
(at 2.5 $m^2$/person) = 45 people
(at 3.0 $m^2$/person) = 38 people
(at 3.5 $m^2$/person) = 32 people
(at 4.0 $m^2$/person) = 28 people

**3) Actual Population Range Estimates**

From the space per capita studies discussed in Appendix III.1, variable densities have been determined (Spafford 1991:24) which consider evidence from the excavation of the three study housepit sites. These variable densities yield a probable population range for each housepit as follows:

HP 90 = 9 to 12
*[24.6$m^2$ ÷ (2.73$m^2$/person to 2.05$m^2$/person)]*

HP 12 = 15 to 25
*[30.7$m^2$ ÷ (2.04$m^2$/person to 1.23$m^2$/person)]*

HP 7 = 37 to 56
*[113.1$m^2$ ÷ (3.05$m^2$/person to 2.01$m^2$/person)]*

# Appendix IV — Total Heat Gain From People

**1) Occupant Heat Gain from Population Estimates (Fixed Densities) (occupant heat gain [from II.3] × specific population [from III.1])**

HP 90
*lower range:* 90W/person × 12 people = 1080W
*upper range:* 107W/person × 12 people = 1284W
*range:* *1080W to 1284W*

HP 12
*lower range:* 90W/person × 15 people = 1350W
*upper range:* 107W/person × 15 people = 1605W
*range:* *1350W to 1605W*

HP 7
*lower range:* 90W/person × 45 people = 4050W
*upper range:* 107/person × 45 people = 4815W
*range:* *4050W to 4815W*

**2) Occupant Heat Gain from Population Estimates (Range of Densities) (occupant heat gain [from II.3] × specific population [from III.2])**

HP 90
1.0 $m^2$/person 25 people × (90W–107W/person) = 2250W to 2675W
1.5 $m^2$/person 16 people × (90W–107W/person) = 1440W to 1712W
2.0 $m^2$/person 12 people × (90W–107W/person) = 1080W to 1284W
2.5 $m^2$/person 10 people × (90W–107W/person) = 900W to 1070W
3.0 $m^2$/person 8 people × (90W–107W/person) = 720W to 856W
3.5 $m^2$/person 7 people × (90W–107W/person) = 630W to 749W
4.0 $m^2$/person 6 people × (90W–107W/person) = 540W to 642W

HP 7
1.0 $m^2$/person 113 people × (90W–107W/person) = 10170W to 12091W
1.5 $m^2$/person 75 people × (90W–107W/person) = 6750W to 8025W
2.0 $m^2$/person 57 people × (90W–107W/person) = 5130W to 6099W
2.5 $m^2$/person 45 people × (90W–107W/person) = 4050W to 4815W
3.0 $m^2$/person 38 people × (90W–107W/person) = 3420W to 4066W
3.5 $m^2$/person 32 people × (90W–107W/person) = 2880W to 3424W
4.0 $m^2$/person 28 people × (90W–107W/person) = 2520W to 2996W

**3) Occupant Heat Gain from Actual Population Range Estimates (occupant heat gain [from II.3] × population range [from III.3]**

HP 90
*lower range:* 90W/person × 9 people = 810W
*upper range:* 107W/person × 12 people = 1284W
*range:* *810W to 1284W*

HP 12
*lower range:* 90W/person × 15 people = 1350W
*upper range:* 107W/person × 25 people = 2675W
*range:* *1350W to 2675W*

HP 7
*lower range:* 90W/person × 37 people = 3330W
*upper range:* 107/person × 56 people = 5992W
*range:* *3330W to 5992W*

# Appendix V — Area and Volume Calculations for Study Housepits

**1) Area and Volume Calculations for HP 90 (refer to Fig. 1)**

a) Area of Earth Floor (HP 90) (@ 5.60 m diameter) [$A = \pi r^2$]
$A = p(2.80\ m)^2 = 24.6\ m^2$

b) Area of Earth Walls (HP 90) [$A = \pi Dh$]
$A = \pi(5.60\ m)(.50\ m) = 8.8\ m^2$

c) Area of Roof (HP 90) [$A = \pi rs$ (s = slant height of roof, $s^2 = r^2 + h^2$)]
$r = 2.80\ m$
$h = 1.96\ m$
$s = 3.42\ m$
$A = \pi(2.80\ m)(3.42\ m) = 30.1\ m^2$

d) Volume of Structure (HP 90)

i) volume above grade [$V = 1/3\pi r^2(h)$]
$V = 1/3\pi(2.80\ m)^2(1.96\ m)$
$= 16.1\ m^3$

ii) volume below grade [$V = \pi r^2(h)$]
$V = \pi(2.80\ m)^2(.50\ m)$
$= 12.3\ m^3$

iii) total volume of structure
$= 16.1\ m^3 + 12.3\ m^3 = 28.4\ m^3$

**22) Area and Volume Calculations for HP 12 (refer to Fig. 2)**

a) Area of Earth Floor (HP 12) (@ 6.25 m diameter) [$A = \pi r^2$]
$A = \pi(3.125\ m)^2 = 30.7\ m^2$

b) Area of Earth Walls (HP 12) [$A = \pi Dh$]
$A = \pi(6.25\ m)(.35\ m) = 6.9\ m^2$

c) Area of Roof (HP 12) [$A = \pi rs$] (s = slant height of roof, $s^2 = r^2 + h^2$)
$r = 3.125\ m$
$h = 1.80\ m$
$s = 3.61\ m$
$A = \pi(3.125\ m)(3.61\ m) = 35.4\ m^2$

d) Volume of Structure (HP 12)

i) volume above grade [$V = 1/3\pi r^2(h)$]
$V = 1/3\pi(3.125\ m)^2(1.80\ m)$
$= 18.4\ m^3$

ii) volume below grade [$V = \pi r^2(h)$]
$V = \pi(3.125\ m)^2(.35\ m)$
$= 10.7\ m^3$

iii) total volume of structure
$= 18.4\ m^3 + 10.7\ m^3 = 29.1\ m^3$

**3) Area and Volume Calculations for HP 7 (refer to Fig. 3)**

a) Area of Earth Floor (HP 7) (@ 12.00 m diameter) [$A = \pi r^2$]
$A = \pi(6.00\ m)^2 = 113.1\ m^2$

b) Area of Earth Walls (HP 7) = area of cone: 1 (below grade) less area of cone: 2 (below floor)
[$A = \pi rs$ (s = slant height of roof, $s^2 = r^2 + h^2$)]

*cone: 1* $r = (6.00\ m + .75\ m) = 6.75\ m$
$h = (9.60\ m + 1.20\ m) = 10.80\ m$
$s = 12.74\ m$
$A1 = \pi(6.75\ m)(12.74\ m) = 270.2\ m^2$

*cone: 2* $r = (6.00\ m)$
$h = (9.60\ m)$
$s = 1.32\ m$
$A2 = \pi(6.00\ m)(11.32\ m) = 213.4\ m^2$

$Awall = A1 - A2 = 56.8\ m^2$

c) Area of Roof (HP 7) [$A = \pi rs$ (s = slant height of roof, $s^2 = r^2 + h^2$)]
$r = (6.00\ m + .75\ m) = 6.75\ m$
$h = 3.15\ m$
$s = 7.45\ m$
$A = \pi(6.75\ m)(7.45\ m) = 158.0\ m^2$

d) Volume of Structure (HP 7)

i) volume above grade [$V = 1/3\pi r^2(h)$]
$V = 1/3\pi(6.75\ m)^2(3.15\ m) = 150.3\ m^3$

ii) volume below grade = volume of cone: 1 (below grade) less volume of cone: 2 (below floor)
[$V = 1/3\pi r^2(h)$]

*cone: 1* $r = (6.00\ m + .75\ m) = 6.75\ m$
$h = (9.60\ m + 1.20\ m) = 10.80\ m$
$V1 = 1/3\pi(6.75\ m)^2(10.80\ m)$
$= 515.3\ m^2$

*cone: 2* $r = (6.00\ m)$
$h = (9.60\ m)$
$V2 = 1/3\pi(6.00\ m)^2(9.60\ m)$
$= 361.9\ m^2$

V (below grade) $= V1 - V2 = 153.4\ m^2$

iii) total volume of structure
$= 150.3\ m^3 + 153.4\ m^3 = 303.7\ m^3$

# Appendix VI — Heat Loss Calculations

**1) Heat Loss Calculations for HP 90**

a) Heat Loss Through Earth Floor (HP 90)

HP 90 floor area [from V.1.a] = 24.6 $m^2$
[from Ashrae 1989:25.6 table: 4]

at .5 m below grade and @ 5.60 m diameter floor interpolate to get .22W/$m^2$°C

[total floor heat loss = ave heat loss/$m^2$ × floor area ($m^2$)] = .22W/$m^2$°C (24.6 $m^2$)
= *5.4W/°C*

b) Heat loss Through Earth Walls (HP 90)

i) area of wall from 0 m to .3 m below grade [$A = \pi Dh$]

D = 5.60 m
h = 0.30 m
A = $\pi$(5.60 m) (0.30 m) = *5.3 $m^2$*

ii) area of wall from .3 m to .5 m below grade [$A = \pi Dh$]
D = 5.60 m
h = 0.20 m
A = $\pi$(5.60 m) (0.20 m) = 3.5 $m^2$

iii) [Ashrae 1989:25.6 table: 3]

0 m – .3 m below grade: 2.33W/$m^2$°C × 5.3 $m^2$ = 12.3W/°C

.3 m – .5 m below grade: 1.26W/$m^2$°C × 3.5 $m^2$ = 5.1W/°C

total wall heat loss = *17.4W/°C*

c) Total Below Grade Heat Loss (HP 90)

total floor heat loss = 5.4W/°C

total wall heat loss = 17.4W/°C

total below grade heat loss = *22.8W/°C*

design temperature difference [from I.3] = 15.6°C

maximum rate of heat loss below grade floor and walls = 22.8W/°C × 15.6°C = *356W*

d) Heat Loss Through Roof (HP 90)

The following assumptions of roof components have been made based on historical accounts (Teit as cited by Kennedy Bouchard 1987:260) and will be treated as typical for all housepits:

i) outside surface film (6.7 m/s wind at winter)

ii) compact earth on roof (.25 m thick average)

iii) leaves, bark and conifer needles (.05 m thick)

iv) spaced joists (.15 m diameter at 1 m on centre)

v) inside surface film (still air)

Assume top roof opening closed with a cover (mat, skin, or other) and a covered lower exit allowing some infiltration air.

i) outside surface film [from Ashrae 1989:22.2 table: 1]
= *.030 $m^2$°C/W*

ii) compact soil on roof (.25 m thick average) comparable: "Chena River gravel" [Ashrae 1989:22.21 table: 12]

thermal conductivity (k) = 1.3W/m°C

thermal resistivity (r) = 1/k = .769 m°C/W

thermal resistance (R) = r × thickness
= .769 m°C/W (.25 m)
= *.192 $m^2$°C/W*

iii) leaves, bark, and conifer needles (.05 m thick) comparable: "sawdust and shavings" [Stein and Reynolds 1992: table: 4.2]

thermal resistivity(r) = 15.39 m°C/W

thermal resistance(R) = 15.39 m°C/W (.05 m)
= *.770 $m^2$°C/W*

iv) decking of aspen saplings laid tight (.10 m dia) comparable: "birch" [from Ashrae 1989:22.9 table: 4]

thermal conductivity (k) = .171W/m°C

thermal resistivity (r) = 1/k = 5.85 m°C/W

area of 1 sapling = .0079 $m^2$

rectangle of similar area = .0079 $m^2$/.10 m
= .079 m

thermal resistance(R) = 5.85 m°C/W (.079 m)
= *.462 $m^2$°C/W*

v) spaced joists (.15 m dia @ 1 m o.c.) comparable: "D.fir" [from Ashrae 1989:22.9 table:4]

thermal conductivity(k) = .141W/m°C

thermal resistivity(r) = 1/k = 7.09 m°C/W

area of 1 joist = .0177 $m^2$

rectangle of similar area = .0177 $m^2$/.15 m
= .118 m

spacing factor 1 m spacing/.15 m = 6.66 spaces/m

ave. continuous thickness = .118 m/6.66 = .0177 m

thermal resistance(R) = 7.09 m°C/W (.0177 m)
= *.126 $m^2$°C/W*

vi) inside surface film [from Ashrae 1989:22.2 table: 1]
= .110 $m^2$°C/W

vii) sum of thermal resistance values (ΣR)
(.030 + .192 + .770 + .462 + .126 + .110)
= 1.690 $m^2$°C/W

thermal transmittance (U)
U = 1/ΣR = 1/1.690 $m^2$°C/W
= *.592W/$m^2$°C*

viii) maximum rate of heat loss(Q) through roof [Q = U × A × ($T_i$ - $T_o$)]
$T_{inside}$ = 5 to 10°C [from I.4]
$T_{outside}$ = -25°C [from I.1]
U = .592W/$m^2$°C [from VI.7]
A = 30.1 $m^2$ [from V.1.3]

*lower range:*
Q = (.592W/$m^2$°C) (30.1 $m^2$) (5°C - (-25°C))
= 534.6W

*upper range:*
Q = (.592W/$m^2$°C) (30.1 $m^2$) (10°C - (-25°C))
= 623.7W

*range:* 535W to 624W

e) Heat Loss Due to Infiltration (HP 90)

assuming air leakage out past covered top entry and infiltration air leaking in through covered side entry

number of air changes per hour (N) in North American house construction ranges from .2/h (tight) to 2.0/h (leaky) [Ashrae 1989:23.9]

assume appropriate range for housepits would fall within .75/h to 1.5/h

using air change method [from Ashrae 1989:25.9] [Q = 1/3(N)(V)($t_i$-$t_o$)]
Q = heat loss(W)
N = air changes/hr (.75/h to 1.5/h) [from VI.1.e]
V = volume of room (28.4 $m^3$) [from V.1.d.iii]
$t_i$ = inside design temp (5 to 10°C) [from I.4]
$t_o$ = outside design temp (-25°C) [from I.1]

*lower range:*
Q = 1/3 (.75/h) (28.4 $m^3$) (5°C - (-25°C))
= 213.0W

*upper range:*
Q = 1/3 (1.5/h)(28.4 $m^3$) (10°C - (-25°C))
= 497.0W

*range:* 213W to 497W

f) Maximum Rate of Total Heat Loss from HP 90

*lower range:*
walls and floor = 356W
roof = 535W
infiltration = 213W
total lower range = 1104W

*upper range:*
walls and floor = 356W
roof = 642W
infiltration = 497W
total upper range = 1495W

*range:* 1104W to 1495W

**2) Heat Loss Calculations for HP 12**

a) Heat Loss Through Earth Floor (HP 12)

HP 12 floor area [from V.2.a] = 30.7 $m^2$

[from Ashrae 1989:25.6 table: 4]

at .35 m below grade and @ 6.25 m diameter floor interpolate to get .22W/$m^2$°C

total floor heat loss = ave heat loss/$m^2$ × floor area ($m^2$)
= .22W/$m^2$°C (30.7 $m^2$) = *6.8W/°C*

b) Heat loss Through Earth Walls (HP 12)

i) area of wall from 0 m to .35 m below grade [A = πDh]
D = 6.25 m
h = .35 m
A = π(6.25 m) (.35 m) = 6.9 $m^2$

ii) [Ashrae 1989:25.6 table: 3]
0 m – .35 m below grade: 2.33W/$m^2$°C × 6.9 $m^2$ = 16.1W/°C
total wall heat loss = *16.1W/°C*

c) Total Below Grade Heat Loss (HP 12)

total floor heat loss = 6.8W/°C

total wall heat loss = 16.1W/°C

total below grade heat loss = *22.9W/°C*

design temperature difference [from I.3] = 15.6°C

maximum rate of heat loss below grade floor and walls = 22.9W/°C × 15.6°C = *357W*

d) Heat Loss Through Roof (HP 12)

refer to section VI.1.d (HP 90 roof heat loss calculations) for typical roof component descriptions and their thermal properties which are considered typical for all housepits

maximum rate of heat loss(Q) through roof [Q = U × A × ($T_i$ - $T_o$)]

$T_{inside}$ = 5 to 10°C [from I.4]
$T_{outside}$ = -25°C [from I.1]
U = .592W/m$^2$°C [from VI.6]
A = 35.4 m$^2$ [from V.2.c]

*lower range:*
Q = (.592W/m$^2$°C) (35.4 m$^2$) (5°C - (-25°C))
= 628.7W

*upper range:*
Q = (.592W/m$^2$°C) (35.4 m$^2$) (10°C - (-25°C))
= 733.5W

*range: 629W to 734W*

e) Heat Loss Due to Infiltration (HP 12) [refer to assumptions F.1.e] using air change method [from Ashrae 1989:25.9] [Q = 1/3(N)(V)($t_i$-$t_o$)]

Q = heat loss (W)
N = air changes/hr (.75/h to 1.5/h) [from VI.1.e]
V = volume of room (29.1 m$^3$) [from V.2.d.iii]
$t_i$ = inside design temp (5 to 10°C) [from I.4]
$t_o$ = outside design temp (-25°C) [from I.1]

*lower range:*
Q = 1/3 (.75/h) (29.1 m$^3$) (5°C - (-25°C))
= 218.3W

*upper range:*
Q = 1/3 (1.5/h) (29.1 m$^3$) (10°C - (-25°C))
= 509.3W

*range: 218W to 509W*

f) Maximum Rate of Total Heat Loss From HP 12

*lower range:*
walls and floor = 357W
roof = 629W
infiltration = 218W
total lower range = 1204W

*upper range:*
walls and floor = 357W
roof = 734W
infiltration = 509W
total upper range = 1600W

*range: 1204W to 1600W*

### 3) Heat Loss Calculations for HP 7

a) Heat Loss Through Earth Floor (HP 7)

HP 7 floor area [from V.3.c] = 113.1 m$^2$

[from Ashrae 1989:25.6 table: 4]

if floor was a square of same area it would have a side dimension of 10.6 m, therefore from table: 4 use 10.5 m (shortest width)

at 1.20 m below grade interpolate to get .13W/m$^2$°C

total floor heat loss = ave heat loss/m$^2$ × floor area (m$^2$)
= .13W/m$^2$°C(113.1 m$^2$) = *14.7W/°C*

b) Heat loss Through Earth Walls (HP 7)

i) area of wall from 0 m to .3 m below grade

surface area of total cone below grade [A = πrs]

r = (6.00 m + .75 m) = 6.75 m
h = (9.60 m + 1.20 m) = 10.80 m
s = 12.74 m (slant height of cone where $s^2 = r^2 + h^2$)
A = π(6.75 m) (12.74 m)
= 270.2 m$^2$

surface area of total cone below .30 m deep

r = 6.56 m
h = (10.80 m - .30 m) = 10.50 m
s = 12.38 m
A = π(6.56 m) (12.38 m)
= 255.1 m$^2$

area of wall from 0 to .3 m deep
= 270.2 m - 255.1 = 15.1 m$^2$

ii) area of wall from .3 m to .6 m below grade

surface area of total cone below .3 m deep = 255.1 m$^2$

surface area of total cone below .60 m deep

r = 6.38 m
h = (10.80 m - .60 m) = 10.20 m
s = 12.03 m
A = π(6.38 m) (12.03 m)
= 241.1 m$^2$

area of wall from .3 to .6 m deep
= 255.1 m - 241.1 = 14.0 m$^2$

iii) area of wall from .6 m to .9 m below grade

surface area of total cone below .6 m deep = 241.1 m$^2$

surface area of total cone below .90 m deep

r = 6.19 m
h = (10.80 m - .90 m) = 9.90 m
s = 11.68 m
A = π(6.19 m) (11.68 m)
= 227.2 m$^2$

area of wall from .6 to .9 m deep
= 241.1 m - 227.2 m = 13.9 m$^2$

iv) area of wall from .9 m to 1.2 m below grade

surface area of total cone below .9 m deep = 227.2 m$^2$

surface area of total cone below 1.20 m deep

r = 6.00 m

h = 9.60 m
s = 11.32 m
A = $\pi$(6.00 m) (11.32 m)
= 213.4 $m^2$

area of wall from .9 to 1.2 m deep
= 227.2 m - 213.4 m = 13.8 $m^2$

v) [Ashrae 1989:25.6 table: 3]
0 m – .3 m below grade: 2.33W/$m^2$°C × 15.1 $m^2$ = 35.2W/°C
.3 m – .6 m below grade: 1.26W/$m^2$°C × 14.2 $m^2$ = 17.9W/°C
.6 m – .9 m below grade: 0.88W/$m^2$°C × 13.9 $m^2$ = 12.2W/°C
.9 m – 1.2 m below grade: .67W/$m^2$°C × 13.8 $m^2$ = 9.3W/°C
total wall heat loss = *74.6W/°C*

c) Total Below Grade Heat Loss (HP 7)

total floor heat loss = 14.7W/°C

total wall heat loss = 74.6W/°C

total below grade heat loss = *89.3W/°C*

design temperature difference [from I.3] = 15.6°C

maximum rate of heat loss below grade floor and walls

= 89.3W/°C × 15.6°C = *1393W*

d) Heat Loss Through Roof (HP 7)

refer to section VI.1.d (HP 90 roof heat loss calculations) for typical roof component descriptions and their thermal properties which are considered typical for all housepits

i) maximum rate of heat loss(Q) through roof [Q = U × A × ($T_i$ - $T_o$)]

$T_{inside}$ = 5 to 10°C [from I.4]

$T_{outside}$ = -25°C [from I.1]

U = .592W/$m^2$°C [from VI.6]

A = 158.0 $m^2$ [from V.3.c]

*lower range:*
Q = (.592W/$m^2$°C) (158.0 $m^2$) (5°C - (-25°C))
= 2806.5W

*upper range:*
Q = (.592W/$m^2$°C) (158.0 $m^2$) (10°C - (-25°C))
= 3273.8W

*range: 2807W to 3274W*

e) Heat Loss Due to Infiltration (HP 7) [refer to assumptions VI.1.e] using air change method [from Ashrae 1989:25.9] [Q = 1/3(N)(V)($t_i$ - $t_o$)]

Q = heat loss (W)
N = air changes/hr (.75/h to 1.5/h) [from VI.1.e]
V = volume of room (303.7 $m^3$) [from V.3.d.iii]
$t_i$ = inside design temp (5 to 10°C) [from I.4]
$t_o$ = outside design temp (-25°C) [from I.1]

*lower range:*
Q = 1/3 (.75/h) (303.7 $m^3$) (5°C - (-25°C))
= 2277.8W

*upper range:*
Q = 1/3 (1.5/h) (303.7 $m^3$) (10°C - (-25°C))
= 5314.8W

*range: 2278W to 5315W*

f) Maximum Rate of Total Heat Loss from HP 7

*lower range:*
walls and floor = 1393W
roof = 2807W
infiltration = 2278W
total lower range = 6478W

*upper range:*
walls and floor = 1393W
roof = 3274W
infiltration = 5315W
total upper range = 9982W

*range: 6478W to 9982W*

**4) Summary of Heat Loss Values for Study Housepits**

a) Heat loss range of components (Watts) and total heat loss.

i) HP 90
walls and floor = 356W (*from VI.1.c*)
roof = 535–642W (*from VI.1.d.viii*)
infiltration = 213–497W (*from VI.1.e*)
*total heat loss = 1104–1495W (from VI.1.f)*

ii) HP 12
walls and floor = 357W (*from VI.2.c*)
roof = 629–734W (*from VI.2.d*)
infiltration = 218–509W (*from VI.2.e*)
*total heat loss = 1204–1600W (from VI.2.f)*

iii) HP 7
walls and floor = 1393W (*from VI.3.c*)
roof = 2807–3274W (*from VI.3.d*)
infiltration = 2278–5315W (*from VI.3.e*)
*total heat loss = 6478–9982W (from VI.3.f)*

b) (Percent Range) and [Percent Average] of Heat Loss by Components *(from VI.4.a) (component heat loss as percentage of total heat loss and [average of percentage range]*

i) HP 90

| | | |
|---|---|---|
| walls and floor | (24–32%) | [28%] |
| roof | (43–49%) | [46%] |
| infiltration | (19–33%) | [26%] |

ii) HP 12

| | | |
|---|---|---|
| walls and floor | (22–30%) | [26%] |
| roof | (46–52%) | [49%] |
| infiltration | (18–32%) | [25%] |

iii) HP 7

| | | |
|---|---|---|
| walls and floor | (14–22%) | [18%] |
| roof | (33–43%) | [38%] |
| infiltration | (35–53%) | [44%] |