Investigation into Heat Loss in Cold Climate Emergency Shelters: Development of an Occupancy Model and Infiltration testing

by

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merit

"I hereby declare that, except where specifically indicated, the work submitted herein is my own original work."

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Introduction

This project is being carried out collaboration with *shelterproject*, a not for profit group developing an insulating liner for humanitarian aid tents. This project is part of a larger series of field tests looking at the thermal and moisture performance of different liner insulation types; it focuses upon two areas:

- Development of an occupancy model

To simulate the water vapour, heat and mechanical mixing produced by the tent occupants. This model has been used in all liner performance tests and is described in the first section.

- Investigation into heat loss through infiltration

Defined as unplanned air leakage, with airflow occurring both through the tent material and through cracks in the tent structure causing heat loss and wind chill. Infiltration is driven by wind and stack pressure. In the second section of this project, infiltration rates are measured for different liner types and conditions. Experimental results are compared to theory and the relative importance of infiltration compared to other mechanisms of heat loss quantified.

Occupancy model

Design parameters for the model were based upon previous field experience of *shelterproject* members in Afghanistan and Kosovo, the CIBSE Guide and humanitarian guidelines. The model developed in this work aims to use a diffuse heat source and to produce dispersed water vapour at body temperature. A number of alternatives were investigated. The chosen design was a well-lagged water bath, at constant body temperature of 37°C, with a float switch to turn off the immersion heater when a preset volume of water has evaporated. Nine water tanks were produced. A number of trial runs were carried out to evaluate the performance of the occupancy model. It was found that; the power input into each tent is not constant or comparable and the latent power makes up a disproportionably large percentage of the power output from the tank, however the radiative / conductive split is approximately representative of a person. Different rates of evaporation meant that comparisons of moisture levels in different liners could only be made over a period of days. Although it has many limitations, this design satisfies the very basic design criteria of being a cheap and simple method of producing a fixed amount of dispersed low temperature vapour.

Infiltration

Two different methods of measuring infiltration were investigated, pressure testing and tracer gas testing. Pressure testing was found not to be suitable for testing a structure as delicate as a tent and so this method was discarded after a short testing period.

Tracer Gas testing

Tracer gas testing deduces the instantaneous air change rate in a space by homogenously mixing a detectable gas with air and recording the decay in concentration over time. Tracer gas tests were carried out for varying stack pressures and wind speeds. Findings were as follows:

- The results found fit reasonably to a relationship derived from a simplified model of airflow in the tent.
- Infiltration forms up to 50% of heat loss in an uninsulated tent. The addition of a liner reduces the heat loss due to infiltration to 10% of the total power input in still conditions.
- Reductions in infiltration due to the addition of an impermeable liner were up to 92% in still conditions with varying stack pressure and 38% for zero stack pressure and varying wind speed.
- Under realistic conditions, wind driven infiltration is far more significant than the effect of stack pressures. This effect is accentuated by the addition of a liner, as stack driven infiltration rate plateaus at a low level. Considering camp planning to minimise wind driven infiltration can be almost as important in reducing infiltration rates as providing an impermeable liner.
- The 50gm^{-2} air impermeable liner is the most efficient, in terms of weight and volume, of those tested at reducing infiltration rates and providing a comfortable environment. This result is backed up by personal experiences in field trials in freezing conditions on a glacier in Switzerland this month. A tent with this liner was comfortable with only the casual gains. The use of this liner could save up to 8.4kg of wood, or the equivalent, per day in extreme conditions. Current air change rates using this liner, however, can be below minimum rates for carbon dioxide accumulation and its use could pose a health hazard. To make the liners habitable a natural ventilation system needs to be designed which can be controlled by occupants to give the required minimum ventilation rate.

1.0 Contents

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Introduction

This project is being carried out collaboration with *shelterproject*, a not for profit group researching transitional settlement for displaced persons. *shelterproject* are developing an insulating liner for the UNHCR (United Nations High Commissioner for Refugees) and ICRC (International Committee of the Red Cross) tents. This work is motivated by recent crises in the Balkans and Afghanistan that have highlighted the need for emergency shelter to be suitable to cold climates; in December 2002 the United Nations began an urgent review of winter aid in Afghanistan after the deaths from cold of 10 children in a refugee camp*[1]. Warmth and protection from cold climates are an integral part of mitigating strategies for people displaced by conflict and natural disasters*[2]. The standard canvas aid tents distributed are inherently leaky structures with low insulation value and little thermal mass. Fuel is often scarce and expensive*[3].

Previous tests indicate that insulating standard aid tents can produce significant improvements in the internal thermal environment and reduction in fuel consumption*[4]. Further field-testing in the UK is being carried out to refine the liner design and specification.

Figure 1: Liner in use, Afghanistan

photo supplied by Joseph Ashmore

This project focuses upon heat loss due to infiltration in tented environments and the development of an occupancy model to simulate the impacts of people on a tent environment. It is part of a larger series of field tests looking at the thermal and moisture performance of different liner insulation types; nine tents with different liners have been tested in parallel over a period of 10 days. Three liners were then selected for further testing on a glacier in Switzerland to consolidate data for thermal and moisture performance in a cold climate. The effect of varying the thickness and permeability of the liner has been investigated and low and high tech materials, i.e. Oxfam blankets vs. polyester composite, compared. The liners are made up of polyester wadding, normally sandwiched with spun-bonded plastic membrane outer layers. All of the membranes used in this experiment are impermeable to air, but have varying permeabilities to water vapour. These tests are attempting to model real life usage as closely as possible. In this report the larger series of tests being carried out by shelterproject are referred to as the vapour performance tests.

Figure 2: Liner materials; with and without membrane outer layers

Heat loss can occur through conduction and radiation through the ground and tent walls as well as air movement through the tent. Infiltration is defined as unplanned air leakage, with airflow occurring both through the tent material and through cracks in the tent structure. In the second section of this project, infiltration rates are measured for different liner types and conditions.

Air movement and heat loss within the tent are affected by water vapour, heat and mechanical mixing produced by the occupants. It is not possible to have human beings living in each of the nine tents for the full testing period and having real human occupants would introduce many aspects of uncertainty, so their impact on the tent environment must be simulated. In the first section of this project, therefore an occupancy model is developed and will be used to represent refugee families in vapour performance tests in the UK and Switzerland.

The following aims have been developed:

- Develop a greater understanding of heat loss in emergency shelters, with particular focus on air change rates and air movement.
- Quantify the importance of heat loss due to infiltration when compared to losses by conduction through the tent walls and to the floor, and by radiation, under known conditions
- Quantify the reduction in heat loss due to infiltration through the addition of an insulating liner. Quantify the effect of increasing the thickness of this liner and adding an impermeable barrier.
- Identify the most important factors affecting infiltration and quantify how infiltration varies with internal and external conditions, including heat input and wind speed.
- Find to what extent infiltration occurs as diffusion through the walls and roof, if they are made of porous material, or as bulk flow through cracks.
- Identify and develop methods of simulating the heat generation, moisture generation and mixing of air caused by human occupancy.

The ultimate aim of the project is to find ways in which standard aid tents and equipment can be improved, in terms of construction or materials, in order to make the shelter response to an emergency situation more appropriate, efficient and provide people with thermally comfortable shelter. As this work is being carried out for a charity, cost of equipment is a major constraint.

To realise these aims the following activities have been undertaken and are described in sections 3.0 and 4.0:

- Occupancy model for 9 tent tests, spanning one month, in Cambridge
- Infiltration testing in Cambridge and Oxford. Two testing techniques were carried out: pressurisation testing and tracer gas testing.
- Field tests on a glacier in Switzerland

3.0 Section 1 - Occupancy modelling

3.1 Introduction

This section is aiming to simulate the affects of occupants upon the tent environment in terms of heat and moisture production of occupants and activities including cooking and heating. The model will be used to test the thermal and moisture performance of liners.

The number, type and behaviour of occupants will vary greatly between cultures, camps and even within small communities. The model parameters are based upon previous field experience of *shelterproject* members in Afghanistan and Kosovo, CIBSE (Chartered Institute of Building Services Engineers) environmental design guide and humanitarian guidelines. This model aims to be representative of a moderate, approximately typical occupancy. All other situations will be extrapolated from this single case. The parameters of the occupancy model are generalised; the main goals are that the power and vapour inputs of model are known, remain constant throughout the test and do not vary between tents. Given the large number of people that need to be modelled, and logistical constraints, it was decided that the occupancy model should be as simple as possible. Previous occupancy models used by *shelterproject* have involved point sources of heat and boiling water, which have been criticised for being unrealistic*[5]; the radiative output is disproportionably high and water vapour concentrated in a single area. The model developed in this work aims to use a diffuse heat source and to produce dispersed water vapour at body temperature. A boiling kettle and an electric heater will be used to model cooking on a wood stove.

The critical factor in the main tests is the vapour performance of the liners. The vapour performance of the liners will be quantified from build up of moisture inside the tent over the week; quantified in terms of moisture content of the air, averaged over each day and in terms of the bulk increase of weight of the liner over the testing period.

3.2 Basic parameters

A family of five people is assumed, based upon humanitarian occupancy standards*[6], all of who spend most of their time inside the tent because of the cold climate. Washing clothes and cooking are carried out inside the tent. Washing clothes brings in 5kg water per wash, assuming one wash per week. This will be produced using the same low temperature vapour as the occupancy model.

Table 1: Heat and moisture outputs per individual*[7]

	Moisture output (g/hr/person)	**Sensible load (W)**	**Latent load (W)**
Adult	40 - 100	100	15
Child	20 – 50	50	7

The heat outputs of the occupants are taken as being the CIBSE design values for people effectively at rest. The vapour outputs are within the range described above. The sensible load is split into approximately 45% convection and 55% radiation. It is assumed that metabolic rate is approximately proportional to weight, apart from the metabolism of very young children, which is disproportionately high*[8]. This assumption should take into account a range of possible ages. The majority of vapour production is from the lungs, therefore vapour needs to be produced at approximately internal body temperature, 37°C. Minimum and maximum volumes of low temperature vapour required are 170-380g / hour. The total power input of the family is 400W.

Observations in Afghanistan indicated that the average family burnt 6.5kg fuel per week. Assuming a calorific value of wood of 16MJ/kg and an efficiency of 50%, fuel combustion will produce 14kWh and 1.1lt water per day.

3.3 Design Development

3.3.0 Ideas investigated

Heat Production

Electric blankets were decided upon for sensible heat source as they have a power rating approximately equivalent to a person, their exposed surface area is easily controlled, when it has reached a steady state the surface temperature is 27°C (exposed skin temperature) and they also provide some thermal mass.

Vapour production

- Domestic humidifiers

These are a simple method of producing a constant and quantifiable volume of vapour, however they are expensive and a single humidifier does not provide enough vapour for the minimum requirements. A domestic humidifier has relatively high power, 500W, which is greater than the entire power input of the model family.

- Steam injection

Models used in previous occupancy studies had a boiling kettle and peristaltic pump to provide constant vapour input*[7]. The major problem with this model is one of scale; nine occupancy models need to be produced and to procure or hire peristaltic pumps for any period of time would be very expensive. There is also the problem of dispersing vapour in a realistic fashion from a point vapour source. The increase in latent heat between steam and low temperature vapour is negligible, approximately 5%, however the kettle would need to be lagged to prevent high radiative losses from its surfaces.

- A self-regulating system, combining heat and vapour production was developed with a controlled flow of water onto the power source, i.e. electric blanket, at the rate at which evaporation is required.

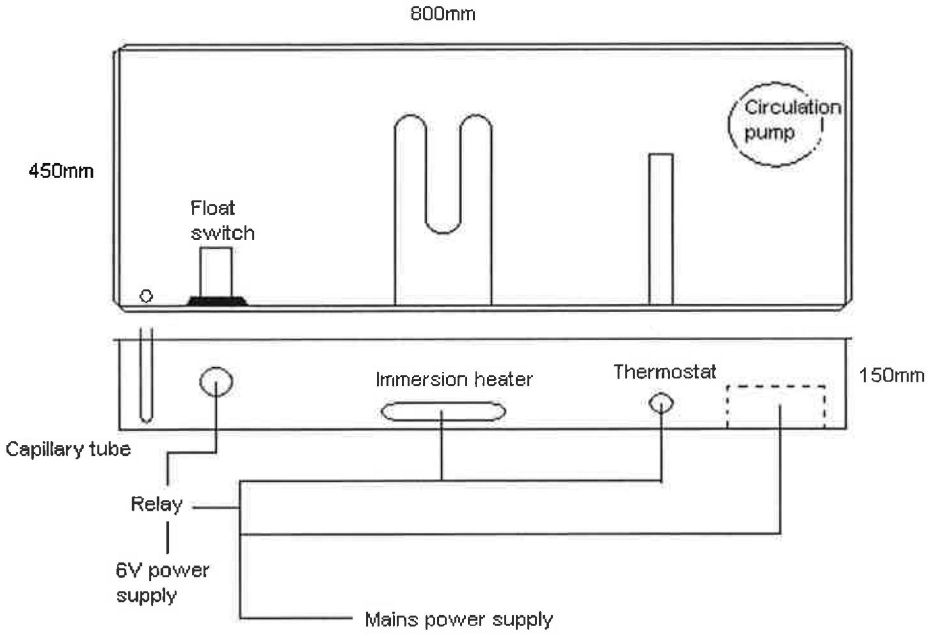
The flow is contained by an additional piece of absorbent material backed by waterproof material to prevent the water reaching the blanket. The water should spread out over the fabric and eventually reach a steady state area so that flow on is equal to evaporation off. If the surrounding conditions change, this steady state area will change. Initial tests were carried out using this method, with the flow provided by a simple constant head system. The water was preheated to 37°C, body temperature, so that there were no sensible heat losses in heating up the water on the plastic sheeting. However it was found that in practice the evaporation rate is not high enough. The experiment was run for 7 hours before ponding of water began. After 10 hours the experiment had to be stopped because of the excessive amount of water on the plastic sheeting. This is partly because of the high heat loss to the floor and partly because the discrete nature of the heating elements meant that only a small proportion of the moisture added came into contact with the heating elements.

- A well-lagged water bath at a constant temperature of 37°C with a float switch to turn off the immersion heater when a preset volume of water has evaporated.

A set amount of water is put into each tent every day. This is constant in every tent. Residual evaporation, after the immersion heater is switched off can be measured and quantified. This solution is simple and cheap, however as evaporation rate is dependent upon many conditions; airflow, humidity, temperature, the evaporation rate will vary between tents, from day to night and over the entire testing period. This water bath will not provide constant evaporation through the day, only a discrete volume in a certain time period. As this will vary from tent to tent, the water bath must be designed so it produces sufficient vapour in the worst case, slowest evaporation, scenario.
A prototype of this idea was built and investigated further.

3.3.1 Prototype

Figure 3: Schematic diagram of tank plan, side and circuit



Heat loss from the water bath occurs by evaporation, conduction and radiation from the water surface. The water is well lagged therefore heat loss through the sides and base is assumed to be negligible.

Heat loss equation*[9]:

$Q = (T_s-T_a)\ A\ k / x\ +\ (T_s^4-T_a^4)\ A\ \sigma\ \varepsilon\ +\ m\ L$

Where:

k = conductivity of air = 0.65

x = distance from the surface for temperature to drop from water surface temperature (T_s) to ambient air temperature (T_a).

σ = Stefan Boltzman constant

ε = emissivity of water = 0.96

m = mass rate of evaporation

L = latent heat of evaporation at 37°C = 2.42MJ/kg

Initially the diffusion equation was used to predict evaporation rates. However this produced unrealistically low rates, as it does not take into account air movement and turbulence, which contributes substantially to evaporation. An empirical equation*[10] was then used, derived from experimentation and dimensional analysis, treating the water bath as being analogous to a still swimming pool.

$W = A(C_1+C_2v)x(P_W-P_{DP})/Y$

where

W = rate of evaporation, kgs^{-1} A = surface area of pool, m^2 C_1= $0.089ms^{-2}$

$C_2 = 0.0782s^{-1}$ V = velocity of air over the surface of the pool, ms^{-1}

P_W = Dew point vapour pressure at surface water temperature, kPa

P_{DP} = Dew point vapour pressure at air temperature, kPa

Y = Latent heat of evaporation, $2416kJkg^{-1}$

This equation indicates that a surface area of water approximately $0.74m^2$ is required to get the maximum evaporation rate, at $v = 0.1ms^{-1}$, water temperature 37°C and internal temperature 20°C.

A small model was built to check this result. Measured evaporation rates were approximately twice as large as those as those predicted, therefore a tank with a surface area of at least $0.37m^2$ is required. However, the size of the tank is restricted by space available within the tent and what size is manageable to fabricate and transport. The final size decided upon was 800 x 450 mm. Depth of the tank was 150mm, the minimum depth to ensure sufficient cover for the immersion heater.

A prototype of this size was then run in the tent. Tests were all carried out in impermeable thick liners to minimise vapour loss in a sheltered environment.
It was assumed that this produces the warmest most humid and still environment and therefore the worst-case, i.e. slowest rate from the water baths. This slowest rate decides the volume which will be evaporated off in all tents within a given time period.

The slowest evaporation rate was found to be around 280g/hour, 26% below the maximum value. It was felt that it would be better to attempt to produce the maximum vapour rather than extrapolate results from lower volumes; therefore, methods to increase the evaporation rate were investigated. This proved problematic as the power input needs to be maintained at realistic levels, i.e. around 400W. A number of methods were looked at to attempt to get maximum vapour production:

- Increasing the temperature to increase evaporation rate. This leads to a sensible load that is much larger than required, as the water bath would need to be at around 43°C to produce the required vapour output.
- Forcing evaporation using fans. To obtain the required evaporation rate significant air movement is required meaning that there would be little stratification within the tent. This is something the vapour performance tests were intending to investigate. The high air movement is also likely to force infiltration, leading to artificial cooling.
- Increasing surface area of water by having slow fans blowing across fins of absorbent material, which hang over the tank and draw warm water up. However the fins are not heated therefore they cool down so quickly that evaporation from them is minimal compared to an open tank at 37deg C.

Eventually it was decided to reduce the evaporation limit and leave the water baths as originally planned. A series of tests were run to find the maximum variance in power input and how this was split between latent, conductive and radiative heat loss. Two extremes were taken; a fully sealed tent with an impermeable liner, and a well ventilated tent with no liner. The results are outlined below.

Table 2: Results from test runs of prototype

Tent /Liner	Power input to tank (W)	Internal tent temperature (°C)	Mass flow rate of water (g/hr)	Latent power per person (W)	Latent proportion of total (%)	Sensible power per adult (W) Conductive / Radiative split (%)	Sensible proportion of total (%)	Variance of sensible load from basic parameters (W)
Impermeable liner	298	12	240	40.31	35	39.1 62 / 38	65	60.9
Impermeable liner	289	12	235	39.31	34	37.5 61 / 39	66	62.5
No liner	564	10	311	53.95	47	101.6 84 / 16	53	-1.62
No liner	416	10	311	53.95	47	59.1 73 / 27	53	40.9
No liner	490	10	243	40.98	36	93.4 83 / 17	64	6.6
No liner	380	10	280	47.98	42	54.9 71 / 29	58	45.1

3.3.2 Final Design

Nine water tanks were produced. Small computer fans were used to disperse the moisture produced to mimic the mixing produced by real occupancy.

Figure 4: Water bath in use,

Experimental set up for vapour performance tests is also shown: stove, sensors, electric blanket and timer switches.

3.4. Discussion of model validity

Please refer to data in table 2:

If there is an increased temperature gradient between the tent air temperature and the water bath temperature, either because of air movement or because the tent is at a lower temperature, the sensible load represented by the water bath can increase massively. This means that power input into each tent is not constant or comparable. It was found to vary by almost 300W. In some cases, the power input to the tent was 160W greater than the maximum required for a model family. In the vapour performance tests, this led to the tanks being used only in the daytime to control their power output.

The latent / sensible split varies greatly from the basic occupancy parameters. The latent power makes up approximately 13% of a persons output*[7] when at rest. Latent power from the water bath makes up between 34 – 47%. This is closer to someone doing vigorous exercise, however it is still unrealistic. The emissivity of water, 0.96, is approximately equal to the emissivity of a person, 0.97, as a weighted mean of clothing and skin*[11]. Therefore the radiative / conductive split is representative of a person when the tent is well sealed. However when airflow over the tank increases, convective heat loss also increases, distorting this relationship.

In the vapour performance tests it was originally intended to enter the tents at hourly intervals. Lids were made for the water baths to minimise further evaporation after the float switches triggered. However, this was found to be too labour-intensive. The difference in switching time between tents varied by up to 3 hours meaning that the vapour input could vary by up to 0.5lt/ day between tents, approximately a 25% variation.

3.5 Results from comparative liner testing

Permeable liners were found to disperse all inputted moisture. Impermeable liners retained 60-70% moisture. The 50gm^{-2} liner, impermeable to air but permeable to moisture, was found to produce significant improvements in thermal performance; increasing the thermal resistance of the liner further returned marginal benefits*[12].

Currently the vapour performance tests are being repeated, with selected liners, on a glacier. Personal involvement in this section was limited to helping set up tents and equipment over the first two days of the expedition.

Figure 5: Tents on glacier

3.6 Conclusion

This design satisfied the very basic design criteria of being a cheap and simple method of producing a fixed amount of dispersed low temperature vapour. However there were many problems with using a water bath as an occupancy model. The primary problem is the uncontrolled sensible load they added to the tent. Residual evaporation led to high levels of variance from tent to tent and the very different rates of evaporation meant that comparisons of instantaneous moisture levels in different liners could not be made, although comparisons over a period of days is possible.

The design could have been much improved by isolating the tank from the tent by placing it outside and having a funnel and well lagged ducting transferring the moisture into the tent. This would have reduced the sensible load and made the evaporation rate more independent of tent conditions. If the users were alerted when the specified amount of water had evaporated off, the tank could be covered, reducing the problems of variance in vapour input. This could be done by including a beeper and a NAND gate in the circuit. Time constraints in this project did not allow for such investigations prior to vapour performance testing.

In retrospect, steam injection or domestic humidifiers, used in isolation from the tent environment, should have been looked at more closely before being discarded on cost grounds.

4.0 Section 2 - Infiltration

4.1 Introduction

Airflow through the tent, in the form of both bulk airflow through cracks and flow through the tent material, is a significant source of heat loss. This section examines the importance of and attempts to quantify heat lost from a tent by infiltration, defined as unplanned air leakage. Ventilation is used to refer to planned air movement, none of the liners or tents tested here have planned ventilation systems.

The expression for heat loss due to air movement*[13] is given below:

$Q_v = V \rho c_p \, dT$

where

V = volume flow rate of air   ρ = density of air c_p= specific heat capacity of air

dT = internal external temperature difference

Thermal comfort is usually defined by appropriate heat exchange between the human body and environment. It has four component parts: air temperature, radiant temperature, relative humidity and air movement. This section of the report focuses upon air movement. It is difficult to quantify an absolute range of environmental parameters for thermal comfort. Comfort is a subjective concept and peoples perceptions of what is comfortable differ between culture and background*[14]. For example, a nomadic people in Afghanistan will be accustomed to a set of conditions intolerable to the majority of people in the UK. Despite these subjective elements, it is reasonable to state that excessive airflow can cause great discomfort. Body heat produces a thin blanketing layer of warm air; wind removes this layer thereby accelerating heat loss, which can lead to frostbite and possibly death. Wind chill temperature, a measure of the combined effect of wind and temperature, can be 2-4°C lower than air temperature*[15] even at a low wind speed of $2ms^{-1}$. Lowering the air velocity in the room permits lower temperatures while maintaining the same degree of comfort*[16].

Obviously there is massive air change when there is a dramatic change, such as a door being opened. In cold conditions, however, this will be brief and the tent very quickly returns to a steady state, where more subtle effects, such as air movement through the tent material and seams, dominate.

An optimum infiltration rate needs to be found so that pollutants in the air are dispersed and condensation is reduced, while comfortable thermal conditions are maintained. The minimum physiological requirements are*[17]:

- To provide a minimum oxygen supply for breathing, approximately 0.009g/s/person; this leads to an air requirement of 0.03l/s/person and a minimum air change rate within the tent of 0.02ac/hour.
- To prevent carbon dioxide produced by breathing from exceeding the maximum permissible level of 0.5%. This leads to an air requirement of 1.25l/s/person and a minimum air change rate within the tent of 1.02ac/hour.

To keep the air fresh and free from bodily odours requires a much higher air change rate, 1.5ac/hour minimum for body odour dilution. However here there is a compromise between thermal comfort and clean air.

Observations in the field emphasise the importance to displaced persons of minimising infiltration; in Afghanistan many people had lashed blankets, a precious commodity in minus 20°C conditions, to the outside of their tents to prevent draughts.

Figure 7: Tents in Afghan camps with blankets outside

photo supplied by Joseph Ashmore

Previous research by *shelterproject* deduced infiltration by using a known power input and the heat transfer equation. The contribution of infiltration to heat loss was estimated at 35%*[18], however this method has high levels of uncertainty. The importance of heat loss through infiltration and how this is affected by changing conditions in real environments is not known accurately.

Infiltration is driven by wind and stack pressure, so will increase under higher wind speeds and greater internal-external temperature differences*[13]. If the tent is modelled as having only four openings, two at each end at the top and bottom of the doors, all with equal area and coefficient of discharge, the basic equations for volumetric air change are as follows:

Buoyancy driven ventilation $V = 2C_d\,A\,[g\,h\,dT\,/\,T_{ave}]^{1/2}$

This is assuming the perfect gas law and small temperature differences. Infiltration is driven by dT, the average difference between internal and external temperatures. This is a square root relationship.

Wind driven ventilation $V = C_d\,U\,A\,[2(C_{p1}-C_{p2})]^{1/2}$

Assuming that wind direction is normal to the tent door. Infiltration varies linearly with wind speed.

where:

C_d = coefficient of discharge, range 0.7 – 1.0

A = area of opening

h = height between openings

U = wind velocity

T_{ave} = ½ (external temperature + internal temperature)

$C_{p1/2}$ = coefficient of pressure on each face of the building with an opening, expressed as a single average value for the whole face.

Wind and stack pressure can act in combination or opposition. The derivation of these equations can be found in the appendix.

To calculate the infiltration rate the size and distribution of openings in the building must be known, this is very difficult to estimate in a tent as leakage occurs throughout the structure and through the tent material. Empirical values for C_d for different types of openings and values of C_p for different types of landscape and building shape are given in the CIBSE guide. However values of C_d are only given for windows, doors etc., none of the values provided are applicable to tents. Values of C_p for a refugee camp are similarly uncertain, accurate evaluation of C_p normally involves wind tunnel tests using a scale model of the building and surroundings. Values given by CIBSE can vary by a factor of three or more. Therefore, the equations quoted above cannot be used and instead direct measurement is required.

Several different methods of measuring air change rate in buildings were researched; pressure and tracer gas testing were chosen for further investigation. These methods provide instantaneous results and are the most widely used in the building industry. Methodologies were developed for both of these tests and materials and equipment sourced. Use of a hot wire anemometer to identify major flow paths in the tent was investigated however this method is not suitable as flow velocities are too slow to measure accurately and the flow direction is ambiguous. Even when held in still conditions the winds speed given by the instrument can vary by +/-0.04m/s because of tiny hand movements. When measuring around narrow cracks turbulence may disturb the flow around the anemometer.

Table 3: Tests being carried out:

Liner type*	**Power input (kW)**	**Wind speed (m/s)**
None	0.0	Ambient
	0.5	Ambient
	1.0	Ambient, 2, 4, 6, 8
	1.0+	Ambient
$50gm^{-2}$ Air impermeable membranes	0.0	Ambient
	0.5	Ambient
	1.0	Ambient, 2, 4, 6, 8
$50gm^{-2}$ No membranes	0.0	Ambient
	0.5	Ambient
	1.0	Ambient
$100gm^{-2}$ Air impermeable membranes	0.0	Ambient
	0.5	Ambient
	1.0	Ambient
$200gm^{-2}$ Air impermeable membranes	0.0	Ambient
	0.5	Ambient
	1.0	Ambient
$200gm^{-2}$ No membranes	0.0	Ambient
	0.5	Ambient
	1.0	Ambient
Plastic tent, no liner	0.0	Ambient
	0.5	Ambient
	1.0	Ambient

*tents are canvas unless stated otherwise

Power input is an electric heater inside a metal stove, mimicking wood burning, and / or electric blankets. Ambient indicates wind speeds below 0.1m/s

The results of these tests will be used in the vapour performance tests to estimate the amount of vapour permeating the liner and the amount being carried out through air movement.

4.2 Pressure testing

4.2.0 Theory and design of experiment

Equipment for pressure testing was very kindly lent to the author by Building Sciences Ltd. Preliminary pressure testing was carried out with and without a liner. As a result of these tests, it was decided that, although the pressure test is much more simple than tracer gas testing, this method should be discarded, for the reasons described on page 26.

The leakage of the tent can be characterised by pressurisation testing. A fan is used to increase the internal pressure of an enclosed environment. The pressure is increased to well over the normal pressures experienced so that the test is independent of climate. The air volume flow rate required to increase the internal-external pressure difference by a specified amount is recorded. A relationship between fan flow rate and pressure difference is determined that gives an indication of leakage per unit area of the tent surface, for a given wind or stack pressure. The major airflow paths can be found using a smoke tracer, and an indication of crack distribution found by temporarily sealing sections and repeating the pressure test. The results can be used to predict infiltration rates in extreme conditions, i.e. high wind speeds and cold climates. *[19]

Before testing began, the following concerns were raised about the suitability of pressure testing as a method of measuring infiltration:

i) Pressure testing is generally used to check building construction quality; it is likely to only give a very rough approximation of infiltration on such a sensitive structure. The characteristic curve of the tent may change dramatically depending upon who constructs the tent or whether the canvas is damp.

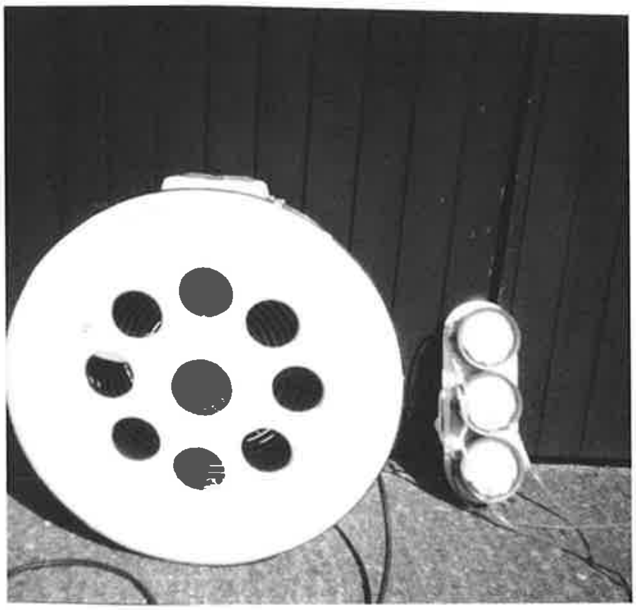
ii) The industry standard test involves reaching pressures of 50Pa; for the test to be independent of climate a minimum pressure range of 15-25Pa should be reached. Under these pressures the tent may deform significantly, affecting its leakage characteristic. However, even if 15Pa is not reached the results may still be valid, as the test will be well sheltered and pressure differences between inside and outside of the tent are much smaller than standard buildings.

ii) The deformation caused by the pressurisation may be permanent. If ropes are gradually loosened throughout the testing period then successive tests will not be comparable.

iii) The test assumes the cracks are all evenly distributed; therefore thermal currents are not modelled. Tracer gas testing may have to be carried out to examine the effects of heat input in still conditions.

4.2.1 Methodology

Figure 8: Fan and gauges



The base of the tent is normally completely dug in; in this test digging in is replicated using timber and gravel bags. The fan is sealed into the tent side. A frame, 2mx1m, was built with an impermeable material fitted onto it, which is taped around the fan, to prevent leakage. The sensors and gauges are positioned and zeroed. The fan can be configured to pressurise and depressurise the tent, in these tests both configurations were used and compared. When the tent is depressurised leaks can be identified using a smoke pencil; this is used both for a quantitative assessment of where infiltration is occurring and to check that the ballasting around the base of the tent and sealing around the fan is airtight. At the beginning and end of every test the tent is depressurised and the sealing is checked. The tent is pressurised incrementally. Flow rate is increased, and recorded, the system is allowed to stabilise and the resulting pressure is measured. Pressure is increased up to a limiting value, 60Pa where possible. This limit is given by the distortion of the tent. Once this limit is reached, the pressure is incrementally reduced and readings repeated.

Figure 9: Fan fitted to the side of the tent.

The initial test was repeated at the end of each testing period. If this is significantly different, it will indicate that the tent has undergone some permanent deformation through the test.

4.2.2 Results

Results are summarised here, but are greatly truncated.

The air permeability at the industry standard pressure, 50Pa, and at a possible working pressure, 5Pa, for three of the tests carried out are given below. These are average values over pressurisation and depressurisation tests.

Table 4:

Test Details	**Air permeability @ 50Pa ($m^3/hr/m^2$)**	**Air permeability @ 5Pa ($m^3/hr/m^2$)**
Damp canvas	45.6	9.56
Dry canvas	41.4	13.4
Liner, dry canvas	32.6	7.01

An average 12% difference in air permeability at 50Pa was found between pressurisation and depressurisation tests. Depressurisation tests were observed to pull cracks closed and improve door seals, therefore reducing air permeability. An 8% difference was found in air permeability at 50Pa given from results taken at low pressure and those taken at high pressure. These indicate that the tent is deforming over the time of the test, therefore either the cracks are being distorted or the sealing is not consistent.

Tests using the smoke pencil indicate that significant air movement occurs through the material as well as through the seams and door.

Identical tests at the end and beginning of each testing period showed a difference of less than 5% therefore the tent is not undergoing significant permanent deformation through the test.

Figure 10: Example output from a low-pressure test, depressurisation with a liner. This graph is extrapolated to find an air leakage index of 29 m^3/hr/m^2 at 50Pa.

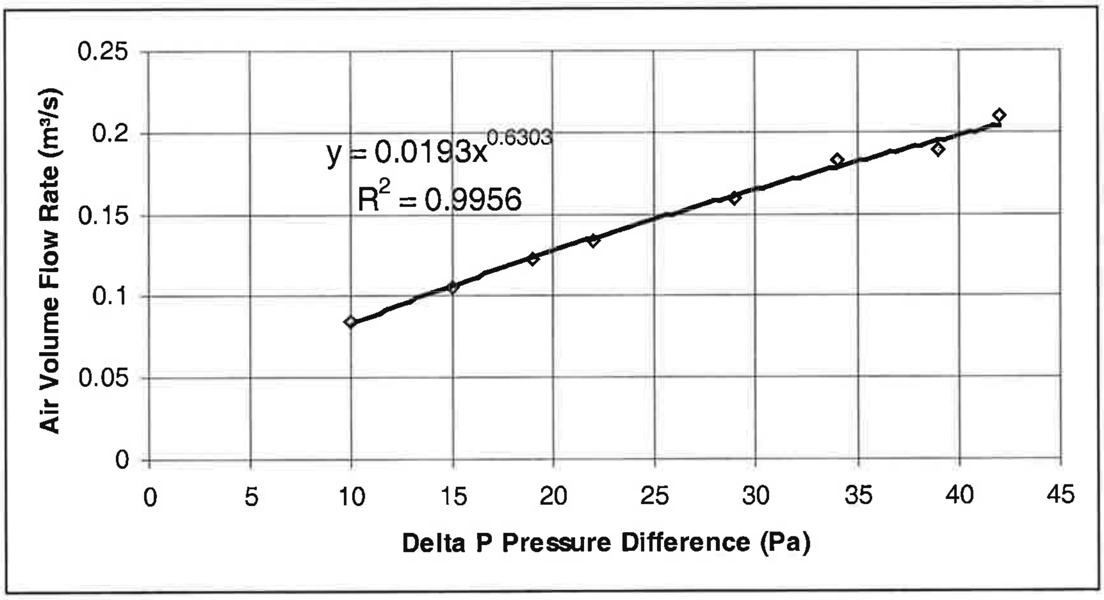
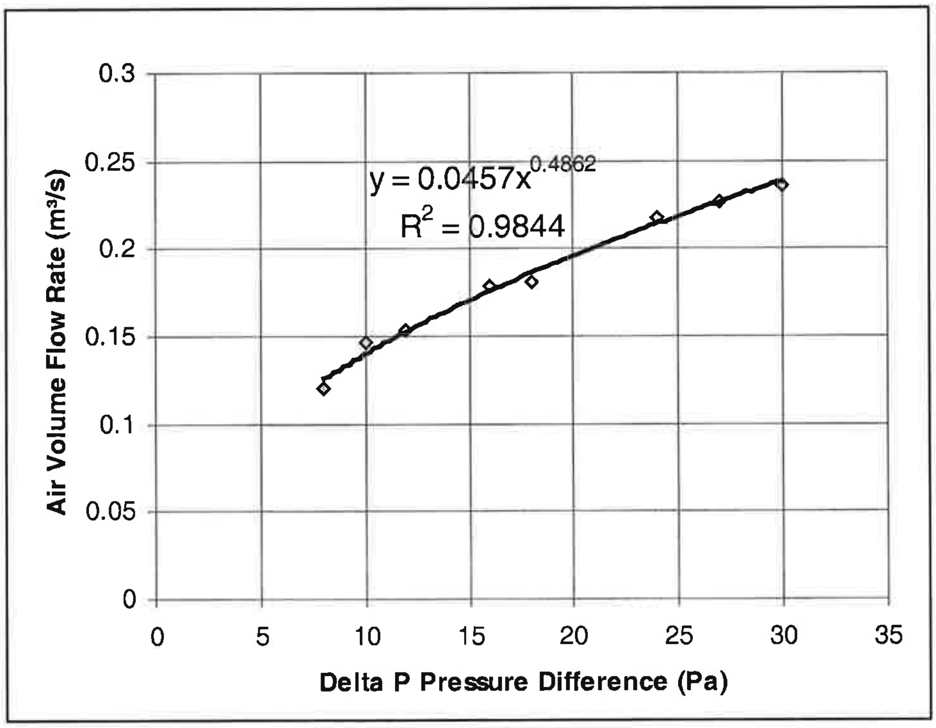


Figure 11: Example output from a low-pressure test, pressurisation with no liner. This gives an air leakage index of 43 m^3/hr/m^2 at 50Pa.



R^2 is a statistical measure of how well a regression line approximates real data points; an R^2 = 1.0 (100%) indicates a perfect fit.

4.2.3 Discussion

Timber and gravel were found to be a reasonable approximation to digging in so will be used for the future tracer gas tests.

These results indicate that the addition of a liner can reduce infiltration rates by up to 52%. However recommended air leakage standards for dwellings are between 15 and 8 $m^3/hr/m^2$ at 50Pa, therefore even with a liner the tent does not comply with any leakage standard. The results also show that at low pressures the moisture content of the canvas can have a significant effect, so air movement through the tent material may be considerable. This result is supported by qualitative observations using the smoke pencil. It is possible that at high pressures this effect is overridden by crack deformation.

Many of the concerns about this method were justified. The tent moves considerably during the test so that sealing and tent construction are altered – leak size is increased with increased pressure. Distortion of the tent is large even under low pressures. The high errors, up to 15%, make it difficult to distinguish changes in results from problems with experimental set-up. For example, the reduction in permeability of damp canvas at low pressures could be either because of changes in porosity or because the damp canvas is heavier and so moves less under low pressures. This method is therefore discarded.

4.3 Tracer gas testing

4.3.0 Theory and Design of Experiment

Tracer gas testing deduces the instantaneous air change rate in a space by homogenously mixing a detectable gas with air and recording its concentration. The test can be done either by recording the decay of a fixed quantity of gas over time, recording the flow rate of gas required to keep the concentration in the air constant or by injecting gas at a known rate and recording concentration. Tracer decay tests will be used; they are the simplest to carry out and analyse, as they do not require the gas injection rate or volume to be measured. In tracer decay tests the concentration of the tracer is plotted against time to produce a regression curve. The data is fitted to:

$$C(t) = C_R \exp(-\lambda_R t)$$

where:

C_R and λ_R are the fit parameters, λ_R = air change rate.

A log graph is then plotted. *[20]

Assumptions:

- Infiltration rate has a constant value over the tracer gas measurement period, so that a graph of ln(concentration) vs. time will produce a linear relationship.
- The total volume of the tent participates in air exchange, so that the measured air change rate multiplied by the volume of the tent gives the total volumetric flow of air through the tent.

Possible tracer gases include sulphur hexaflouride and nitrous oxide. These are completely inert so can be used when the building is occupied. However, they are also very expensive to buy and require expensive mass spectrometers to record concentrations. Instead it was decided to use carbon dioxide as a tracer gas. This is cheap and less damaging to the environment than the alternatives. The use of carbon dioxide as a tracer gas is relatively new; it was developed by the Energy Monitoring Company in 1996 and has been shown to be successful. Standard industry safety sensors can be used which are also cheaper. The major disadvantage is that there is a risk of asphyxiation, however steps are taken in the methodology to mitigate this risk. It is assumed that carbon dioxide levels below 0.5% are completely safe and that at levels at 10% or above are fatal. *[21]

When testing in ambient conditions it is assumed that the site is sheltered enough that changes in wind speed are negligible. Testing with changing wind speed will be done in-situ using a wind machine. Initial measurements carried out at Pinewood Studios, on a 1.6m diameter portable fan, showed that laminar even flow over the height and width of the tent could be reached within a 10m distance. Wind velocities of up to 15m/s can be achieved. The hire of this fan proved to be too expensive and a tent and liner were instead taken to Oxford for wind testing with Building Sciences Ltd, as described in the following section.

Air change rates measured here are dependent upon the external and internal environment. Therefore weather conditions and internal temperatures and power input into the tent must be monitored continuously throughout the test.

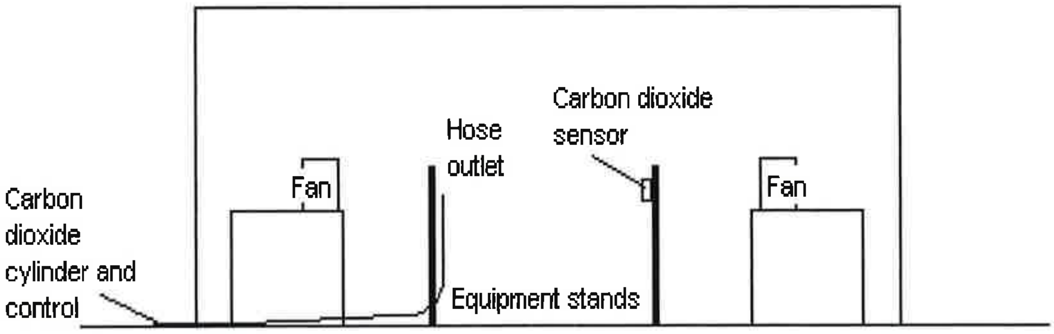
Before this phase of testing began, the following concerns were raised about the testing method:

- Disturbing stratification of temperatures by disturbance of air, air temperatures will be logged at different heights throughout the tests, which will identify if this is a problem.
- Carbon dioxide is 1.5 times the weight of air, therefore it may settle over a longer testing period so that the concentration change does not represent flow of air. This can be checked by comparing repeatability of tests carried out at different levels within the tent.

The results from this section of the report were presented by the author to members of Oxfam, UNHCR, UNHABITAT, RedR, GOAL, MSF, Sphere Project, UNOCHA and many other organisations at the 3rd *shelterproject* peer review meeting in Geneva, May 2003.

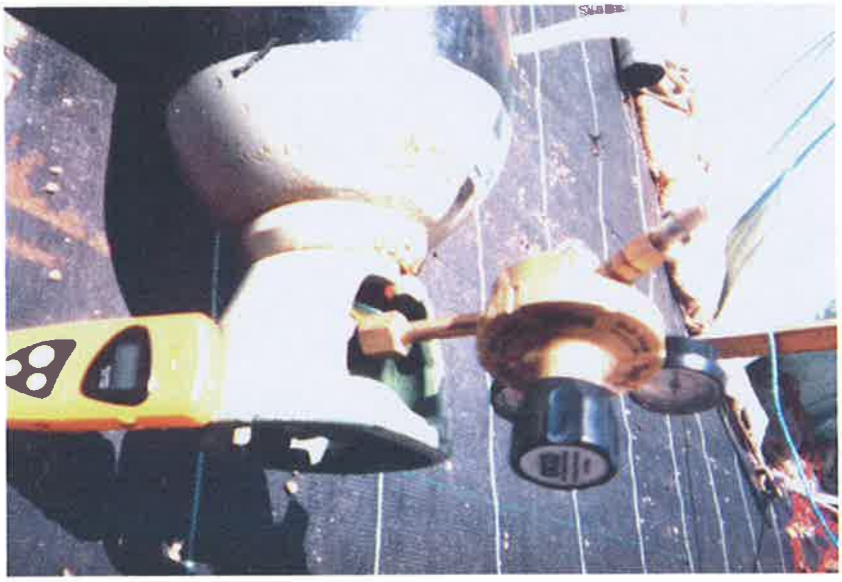
4.3.1 Methodology

Figure 12: Schematic drawing of equipment layout, view of tent in long section



The fan is positioned in front of the hose outlet in order to mix the tracer gas as soon as it enters the tent. Another fan on the opposite side of the tent ensures symmetrical mixing of the gas. Homogenous mixing was checked both by taking readings at various sensor positions, described on page 31, and quantitatively by checking that this fan layout produced air movement in all areas of the tent. The carbon dioxide sensor and data logger are positioned approximately in the centre of the tent. The CO_2 monitor logs continuously so that background levels, and their variance, are also known.

Figure 13: CO_2 sensor and gas regulator



The CO_2 cylinder is positioned outside the tent with the hose attachment reaching inside. The gas canister will be fitted with a regulator so that flow is controlled. Enough tracer gas needs to be released for the concentration within the tent to reach the upper safety limit of the sensor, 1%, however the flow must be slow enough to prevent icing around the nozzle. The sensor beeps intermittently at a CO_2 air concentration of 0.5% and continuously at 1%; this is audible from outside the tent. When any heat input is required, it must be allowed to stabilise for at least 1 hour before the test is begun. Data from a weather station was used throughout the tests to log external conditions. Wind speed is logged every minute. Solar gains are estimated by assuming the lux levels are equal to the values given at the Baker Building weather station and that the efficiency of sunlight is 115 lumens/W.

The air inside the tent is thoroughly mixed while the gas is released. As soon as the 1% alarm is heard, the gas input is stopped and the fan then switched off. The experiment is then run until the concentration of the tracer gas has fallen to below 40% of the original concentration. The gas concentration sensor logs results every 30s. After the test, ventilation is allowed for at least ½ hour so the remainder of the carbon dioxide can disperse. Before entering the tent, an oxygen level sensor will be used to ensure that it is safe.

The temperature profile inside the tent will be logged at ten-minute intervals during each tracer gas test, using five air temperature and humidity sensors. Positions of the sensors were determined as being representative in a previous experiment*. The temperature profile was used to calculate the temperature difference driving the infiltration. Temperatures at each point were be averaged over the time of the test. The temperature profile produced was integrated over the height of the tent in order to find the mean value.

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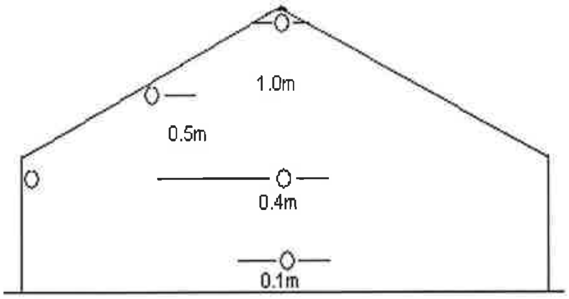
* with Kate Crawford and Rachel Batillana

Figure 14: Sensor layout, cross section through tent centre line



The power input into the tents is measured and recorded over the time of the test so that the proportion of heat lost through infiltration as a percentage of the total power input can be found.

Tests were first carried out to check repeatability and to ensure that mixing of the gas was homogenous throughout the tent. If gas distribution is homogeneous, and realistically modelling the movement of air, then the air change rate measured for a given set of conditions should be the same wherever the sensor is placed. This only holds within the bulk of the tent – i.e. not if the sensor is placed near a large crack with high airflow. The test was repeated with the sensor in three different positions. These results should also indicate whether the assumption that the entire tent is taking part in the air exchange is valid.

Tests were carried out in a plastic tent and with different liners in a canvas tent. Different power inputs were used to create a range of stack pressures.

Building Sciences Ltd kindly lent their trolley fan to the author for a day of testing a liner under varying wind speeds. The lightest, 50g/m^2, impermeable liner was chosen for testing under wind speed as this is being taken for further testing on a glacier. The testing procedure was as described above, however the fan was allowed to reach a steady speed before the gas was released. Wind speed was logged using a manometer and a Squirrel logger. Spot readings were also taken using a handheld anemometer.

Figure 15: Tests with varying wind velocity, wind machine is shown to the right

All tests described here were carried out with an electric heater with no flue pipe for the stove. In the field there is likely to be a number of different types of flue output and either wood burning or kerosene stoves. Any kind of flue used with a material combusting, rather than an electrical heater will significantly increase infiltration rates, because of both increased leakage and the additional draw through of air during combustion. To estimate the effect of this a test was carried out using a paraffin heater and a flue as photographed below. The heater is inside the stove shown in figure 4. The test was first calibrated by measuring the output of CO_2 from the paraffin heater alone. The test was then carried out as normal.

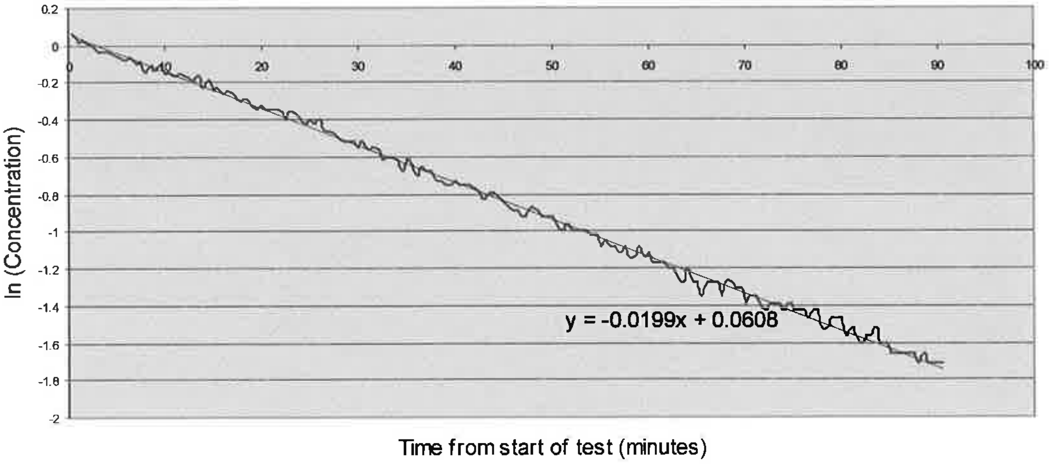
Figure 16: Tent with flue

photo supplied by Sam Clarke

4.3.2 Results

Recorded wind speeds on the site were found to be approximately ambient, 0.1m/s or below; when wind speeds were higher, tests were repeated in still conditions. The temperature loggers used the air temperature every 10 minutes, within this time period from the start of the test temperatures had invariably re-stratified and were in a stable state. The concerns about the test preventing temperature stratification were unfounded. Tests repeated in identical conditions gave air change rates that agreed to within 5%. Tests repeated with the sensor in different positions and heights also agreed to within 5%, showing that the whole tent is taking part in air exchange and the tracer gas is modelling the flow of air. Background levels of CO_2 vary by approximately +/- 0.05%. The tent material was dry in all tracer gas tests. The air change rate was found to be constant over time, giving a constant gradient when the natural log of gas concentration is plotted against time. This is shown below.

Figure 17: Example output for tracer gas test in a plastic tent without liner.



The infiltration rate in air changes per minute is given by the gradient of the graph, 1.2 ac/hour. The tests without liner in canvas often gave results that were more erratic; they are more sensitive to rare increases in wind speed and the tests are much faster so fewer readings are taken. Any deviations from a constant gradient indicate where possible problems might lie and where tests may need to be repeated.

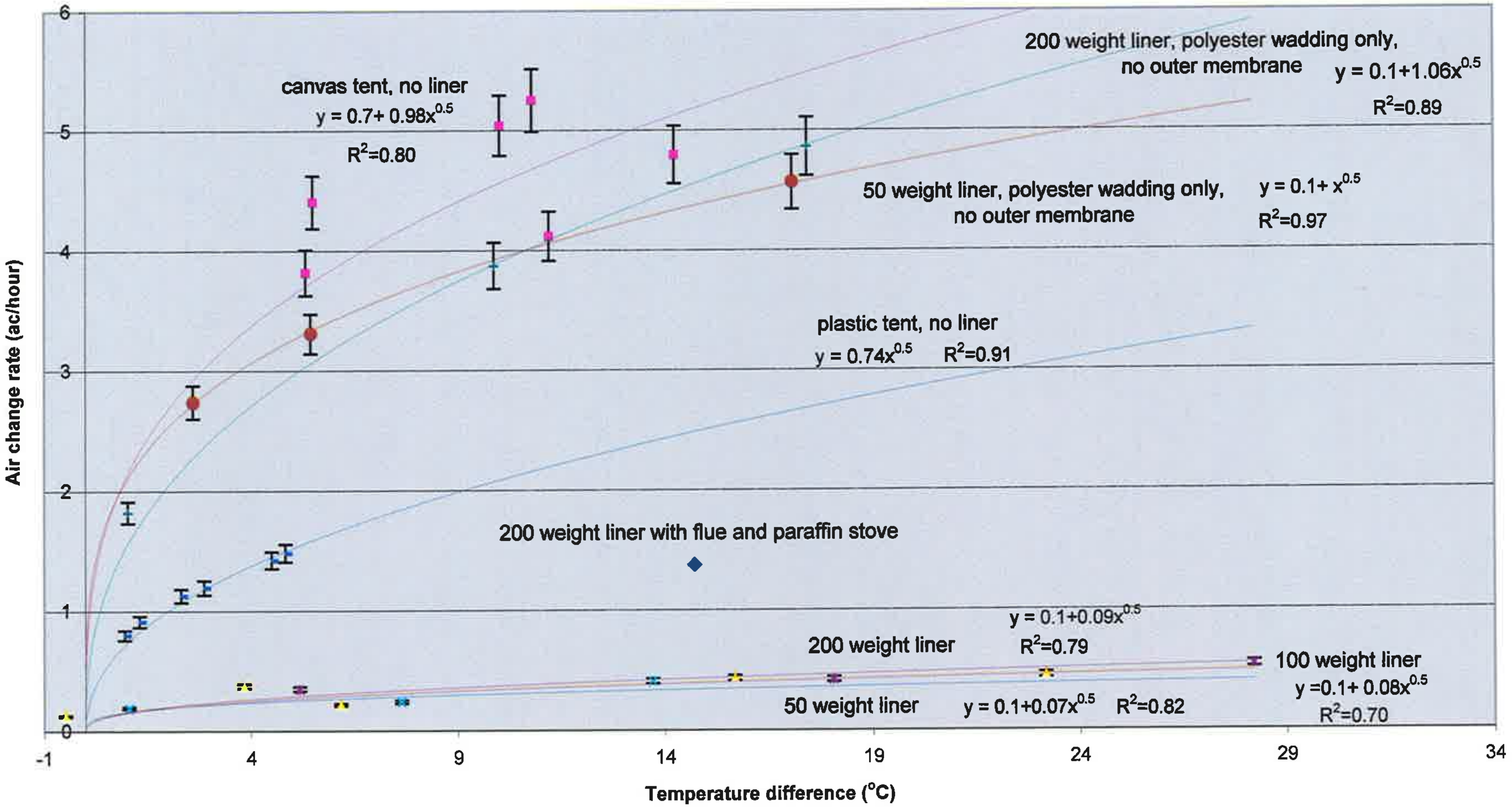
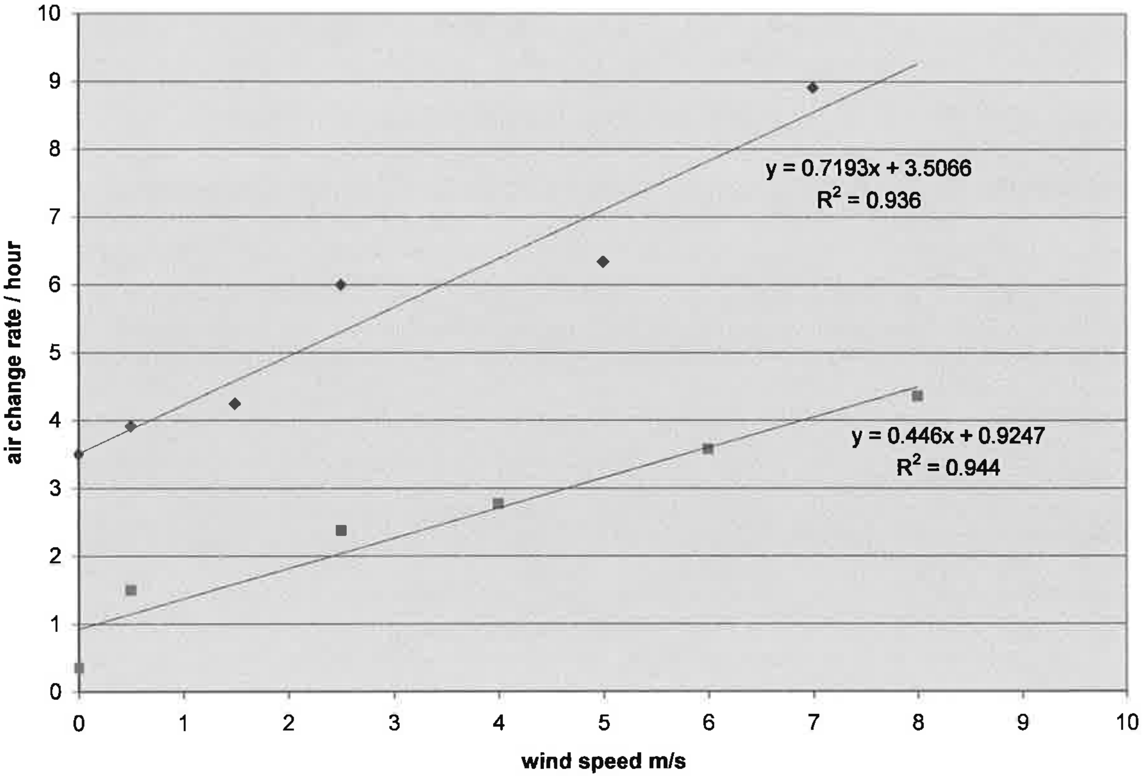


Figure 18: Variation of infiltration rate with stack pressure, in still conditions

It was found that the CO_2 produced by a paraffin stove stabilised at 0.3% in a tent with an impermeable 200g/m^2 liner after 2.5 hours. Therefore, the tracer gas test could be carried out without correction if the tent was left to stabilise for this minimum period.

Figure 19: Variation of infiltration with wind speed, with an approximately constant stack pressure, dT = 5°C +/- 1°C. The liner is 50g/m^2 and impermeable



Power readings and solar gains taken in each test were used to estimate the total power input and therefore contribution of infiltration to total heat loss. Results are greatly truncated; data is only given in this table for one test on each liner. Tests with similar stack pressures are taken for comparative purposes.

Table 5: Heat lost through infiltration in different liners at a comparable temperature difference and in still conditions.

Liner: weight (g/m^2) /permeability	**Steady state dT (°C) still conditions**	**Power input including solar gains (kW)**	**Measured air change rate (ac/hour)**	**Heat lost through infiltration (W)**	**Power lost through infiltration, % of total power input**
200 impermeable	18.1	1.20	0.42	55.6	4.6
100 impermeable	15.7	1.05	0.43	49.7	4.7
50 impermeable	13.7	1.07	0.41	41.0	3.8
None	14.2	2.80	4.80	500.8	17.9
50 permeable	17.1	2.40	4.57	571.9	23.8
200 permeable	17.4	2.20	4.86	621.6	28.3

The power lost through infiltration increases in comparison to other mechanisms of heat loss as the air change rate increases. In an uninsulated or poorly insulated tent under high stack pressures infiltration can make up to 30% of heat loss, under high wind pressures this increases to 50%. With the addition of an impermeable liner infiltration as a proportion of total heat input is reduced to a maximum of 10% and 20% respectively.

4.3.3 Discussion

4.3.3.0 Use of results

Table 6: Use of results: Data to be input into vapour testing to quantify liner performance

Liner: weight (g/m^2) /permeability	**Steady state dT (°C) (still conditions)**	**Predicted air change rate (ac/hour)**	**Heat lost through infiltration (W)**	**Power lost through infiltration as a % of the total power input**
200 impermeable	15.0	0.45	49.5	5.0
100 impermeable	14.5	0.42	44.7	4.5
50 impermeable	12.0	0.37	32.56	3.3
None	4.0	3.55	104.1	10.4
50 permeable	4.5	3.16	104.3	10.4
100 permeable	5.0	3.10	113.7	11.4

The steady state dT is projected for an external temperature of –10°C and a 1kW heat source, this design data was supplied by Rachel Battilana. Infiltration testing was not carried out on the 100 weight permeable liner, the air change rate is extrapolated from results from the 200 weight and 50 weight permeable liners. The predicted heat loss through infiltration will be used to generate a global conductance for the liner material in use. The moisture content of the air inside the tents during the vapour performance tests was recorded and the infiltration testing results will also be used to estimate the amount of water vapour leaving the tent through bulk air flow compared to the amount being absorbed by the liner material.

4.3.3.1 Factors affecting infiltration and agreement between experimental results and theory

Stack pressures:

At an internal external temperature difference of 20°C, the minimum for the tent to be habitable at external temperatures of minus 10°C, the uninsulated tent has an air change rate of 5.75ac/hr in still conditions. Assuming equal sizes and occupancy of five people this is almost four times the recommended air change rate for domestic buildings. Although this indicates that the standard tent has high airflow, with corresponding heat loss and risk of wind chill for the occupants, the recommended air change rate is for western occupants at home and may not translate clearly to adapted values for thermal comfort in a humanitarian emergency. The addition of the lightest, 50gm^{-2} impermeable liner reduces the air change rate in the tent to 0.44ac/hour, a decrease of 92% to a third of the recommended air change rate.

The increase in infiltration rate for a given increase in temperature difference slows as stack pressure increases. This is particularly prevalent with impermeable liners, which plateau at very low level; even at the upper limit of realistic stack pressures, the air change rate does not go above 0.6ac/hour. In an uninsulated tent the maximum air change rate is around 7ac/hour, however an unrealistically high power input is required for the temperature difference to be this high.

Infiltration driven by stack pressure appears to follow the square root relationship predicted, although the actual distribution of openings in the tent and resultant flows will be far more complex than postulated. Values for R^2 are around 0.9 or greater for the plastic tent and permeable liners. Lower R^2 values are given for the impermeable liners, as the measured air change rates are smaller, however the maximum actual deviation for these liners is within 0.07ac/hour. The canvas tent has the largest deviation from the trend line. Tests on a canvas tent with no liner were the first tests to be carried out, remote wind speeds were slightly higher during this period and often insufficient time was allowed for the tent to reach steady state before the tracer gas test was begun. These factors may account for the high levels of variation, particularly in comparison with much later tests on permeable liners. Tests were also carried out over a much shorter temperature range. However, it is reasonable to assume that the test results from a canvas tent without liner will follow a similar relationship to all other results.

Diffusion of carbon dioxide down the concentration gradient has not been quantified. It was originally assumed that it is insignificant, however trend lines fitted to the data almost all have a constant component, which may represent this diffusion. This indicates that the error in air change rate due to this diffusion is around 0.1 ac/hour for an insulated tent and around 0.7 ac/hour in an uninsulated tent. These values are uncertain, however, and may equally be due to low wind speeds or other experimental error. In particular, the difference in this constant value between the tent without a liner and a tent with a permeable liner is questionable, as the permeable liners are shown to offer little resistance to the movement of carbon dioxide. Therefore, they are not taken account of when comparing to the theory below.

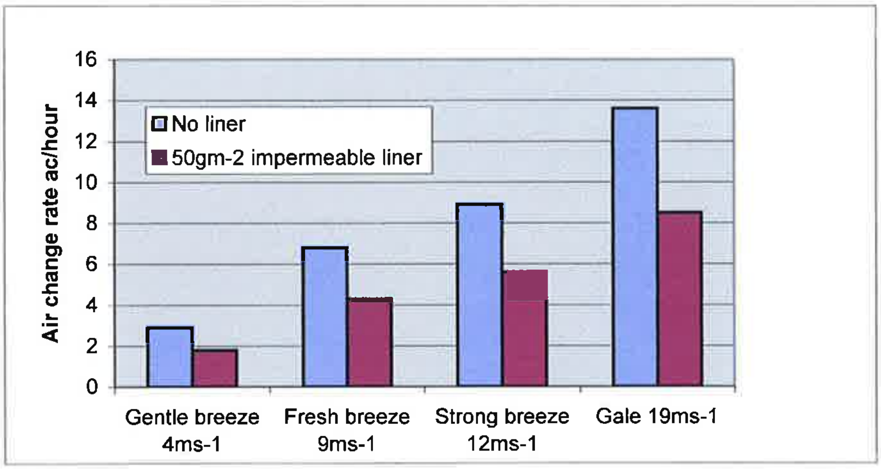
Comparing the trend lines fitted to the data with the equation quoted in section 4.1, page 18 gives the total area of openings in the canvas tent, with or without a permeable liner to be between 1.0m^2 and 1.6m^2. An impermeable liner reduces the total area of openings to between 0.07m^2 and 0.1m^2. These values are within the right order of magnitude and could be used as limiting values in a computational analysis of airflow within the tent. However, as absolute values they are unreliable.

Because of time constraints, the minimum number of tests to postulate a curve was carried out for each liner. To get a more comprehensive picture further testing is required, possibly in a more controlled environment.

Wind pressures:

At an internal external temperature difference of 20°C the additional air change rate for every 1m/s increase in wind speed above ambient, with the wind incident upon the tent door is 0.72 ac/hour for an uninsulated tent and 0.45ac/hour in a tent with the lightest impermeable liner. This is a reduction of 38%. Comparing this to the Beaufort scale gives the following wind driven infiltration rates.

Figure 20:



In the situations measured, the stack and wind pressures act compositely rather than in opposition. Under likely stack and wind pressures the wind velocity will have a much more significant effect than internal external temperature difference. This is accentuated by the addition of a liner, where increases in infiltration rate due to wind are an order of magnitude greater than those caused by stack pressures. These results are taken for a worst-case scenario however, and are likely to be an overestimation. The site this testing was carried out on was very exposed and the tent was set up so the wind was incident on the tent door. In reality, people are unlikely to set up facing into the direction of the prevailing wind and there will often be some kind of windbreak. Because of the range of the coefficients of pressure, as described in section 4.1, the infiltration rates measured here may be reduced by at least 30% in different conditions. Wind driven infiltration rates can be significantly reduced by good site planning. For example; well positioned wind shields, avoiding wind funnels, orientating tents so the longer side is parallel to the direction of the prevailing wind and avoiding low level openings in tents when there are no windbreaks; when low level enclosures, such as tents, are clustered together wind velocity around the base of the buildings is usually low.

During testing, it was observed that the wind produced was gusty and turbulent rather than evenly laminar. Although this meant air change rate in the tent without a liner was quite erratic, it is also a realistic representation of wind conditions.

Infiltration driven by wind pressure follows a linear relationship with wind speed as predicted. Comparing the trend lines fitted to the data with the equation quoted in section 4.1, page 18 gives the total area of openings in the canvas tent, without a liner to be around 2.2m^2, approximately twice the value deduced when testing with only stack pressures. An impermeable liner reduces the total area of openings to around 1.3m^2, an increase of an order of magnitude over stack pressure estimates. This massive increase indicates that substantial deformation of the tent, and the liner inside, is taking place, which may increase errors due to insufficient ballasting and poor construction. Results could possibly have been improved by improving sealing around the base of the liner inside the tent. These areas are derived by assuming values given by the CIBSE guide for exposed situations and the pressure distribution indicated by deformation of the tent during testing, positive on the front face, negative on all other surfaces. Pressure coefficient C_{p1} on the windward face is 0.7 and C_{p2} on the leeward face is –0.2.

4.3.3.2 Importance of infiltration as a mechanism of heat loss

Infiltration is a significant form of heat loss compared to losses through conduction and radiation through ground walls and roof, up to 50% of all heat losses from a canvas tent. It increases in significance relative to conduction and radiation as driving pressures increase and so is far more important in extreme than temperate climates. Addition of an impermeable liner makes infiltration a much less significant mechanism of heat loss, a maximum of 20% of the total power input.

Solar gains introduce some uncertainty in these estimates. Fluctuating solar gains mean that the tent is never truly at steady state and the total power input is difficult to estimate. The data on sunlight hours taken from the Baker building weather station are given for every half hour; this is a longer period than the majority of the tracer gas tests. Direct readings of lux levels were taken during the wind machine tracer gas tests. They were found to vary by up to 50kLux, equivalent to a 7kW variation in power input over the whole footprint of the tent.

However, if conditions are known, power input is measured and the variance in solar gain is eliminated or lux levels logged regularly in real time, then the graphs produced in this report can be used to predict infiltration as a percentage of total power input, as shown in table 6, page 37.

4.3.3.3 Recommended liner for future development

After the significant decrease in infiltration seen with the 50gm^{-2} impermeable liner, increasing the thickness of the liner further has negligible effect. The results actually show a marginal increase in infiltration rate with the use of a 200 or 100 gm^{-2} impermeable liner however this is assumed to be experimental error. Removing the outer membrane of the liner negates any effect it may have on reducing infiltration rates. The reduction in infiltration rates for the 50gm^{-2} and 200gm^{-2} were marginal, 17% and 10% respectively. The membrane of the liner is the controlling factor in reducing infiltration.

The 50gm^{-2} impermeable liner is the most efficient; it minimises the transport and storage costs while providing the same reduction in infiltration as heavier liners. As the liner is less bulky it encroaches less upon the living area, forming a more roomy internal environment. It can be installed more easily and quickly and stored inside the tent; most liners will only be used for a section of the year. The suitability of this liner to use in cold climates was supported by quantitative observations taken while sleeping in the tent on a glacier in Switzerland; using the recommended liner and with the only power input being casual gains from five occupants the internal environment was comfortable in freezing conditions with high wind speeds.

Power savings with chosen liner

The reduction in air change rates due to the addition of the liner lead to significant savings in the power input required to keep the tent at a comfortable temperature in extreme climates; 780W for an internal external temperature difference of 20°C in still conditions and an extra 40W for every 1m/s increase in wind speed. In still conditions, this is equivalent to up to 8.4kg wood per day.

Potential problems

There are potential health problems with the use of every impermeable liner tested here. The maximum air change with the liner in still conditions is approximately half that required to keep carbon dioxide at safe levels i.e. less than 0.5%. The minimum ventilation rate required for a family of five in the tent is 1.02 ac/hour. The impacts of carbon dioxide accumulation can be severe. Although short-term exposure at levels below 2% has no harmful effects, longer-term exposure may cause decreased night vision and colour sensitivity and concentrations greater than 10% can cause vomiting, sweating, stupor within several minutes and loss of consciousness within 15 minutes. The scale of this risk is very low and it can be safely assumed that the occupants will ventilate the tent themselves before this occurs. However, a ventilation system within the tent, which allows a more controlled ventilation method than opening the door, would be beneficial.

4.3.3.4 Effect of the addition of a flue pipe

The infiltration rate in an impermeable 200gm^{-2} liner is increased by 0.94 ac/hour, i.e. almost doubled, at an equivalent stack pressure by the addition of a flue and the use of a paraffin stove. Increases are due to draw through of paraffin stove and possibly leakage from around the flue plate. This increased value is likely to be a more realistic estimate of the infiltration rate if this type of stove and flue are used. However there are massive levels of variation in the types of stove and flue plate and configurations used so this limited investigation gave only an indication of the order of magnitude of effect. Use of carbon dioxide as the tracer gas may cause errors in the results as although the carbon dioxide output of the stove was found to stabilise, the addition of CO2 may affect the combustion of stove. Background levels of carbon dioxide may not be constant, therefore, affecting the result.

The use of a wood or kerosene-burning stove may prove to be an additional health hazard, increasing the steady state carbon dioxide to 0.3% without any human input. However, the additional infiltration it promotes will help to reduce this risk.

4.3.3.5 Airflow pathways

An accurate value for the porosity of canvas and the proportion of air movement through the tent material as opposed to bulk flow through cracks is not known. Instead, it is estimated by comparing infiltration rates in plastic and canvas tents. The comparison assumes that the plastic and canvas tents are identical in construction quality, manufacture and set up, but the material for the plastic tent is effectively impermeable. Use of a plastic tent reduces air change by 55% +/- 5% for stack pressures where temperature difference is greater than 3°C: indicating that around 45% of air flow is through cracks, including seams and base as well as the top and bottom of doors, and 55% through material. In impermeable liners, all airflow must be through cracks in the tent structure, the liner leads to significant improvements in the sealing around cracks.

4.3.3.6 Suitability of testing method

Tracer gas testing is a suitable method for direct measurement of infiltration rate in tents and gives a true picture of air movement, including buoyancy effects, within the tent. It is repeatable to within 5%. The major limitation of this testing method is that, unlike pressure testing which is independent of climate, it only gives results for a specific location and set of conditions. The results obtained in this report, however, can be extrapolated to more extreme conditions, although at present the number of tests done on each liner and tent is so few that any extrapolation outside of the given data points should be carried out with caution. Different incident wind directions and locations need to be looked at before the wind data can be used to predict wind driven infiltration with any confidence outside of the specific test conditions.

As described on page 38 the possible errors introduced by the diffusion of carbon dioxide down the concentration gradient is unknown and an additional drawback of the use of tracer gas testing.

Experimental set-up, including variations in ballasting and construction or manufactured quality between tents and liners, and variations in door sealing between tests, have an impact on results that is difficult to quantify. Carrying out experiments in an uncontrolled environment brings a number of problems; fluctuating solar gains and low wind speeds as mentioned earlier and small variations in the moisture content of canvas introduce uncertainty.

These combined factors may mean that errors in the tests are greater than the 5% originally estimated. Larger expected errors, of up to 10%, while still being within a range acceptable for use of the data in the vapour performance testing will help to explain some anomalies in the results. For example the 200g/m2 permeable liner appears to permit a higher infiltration rate than the 50g/m2 at temperature differences over 10.5^{o}C, which is probably due to experimental error.

4.4 Conclusion and recommendations

Infiltration is a significant form of heat loss. The importance of infiltration compared to conduction and radiation through the tent walls and roof increases with increased air change rate. Infiltration forms up to 50% of heat loss in an uninsulated tent. The addition of a liner reduces the heat loss due to infiltration to 10% of the total power input in still conditions.

Reduction in infiltration due to the addition of an impermeable liner:

- Reduction from 5.75ac/hour to 0.44ac/hour at internal external temperature differences of 20°C
- Reduction of 38% for zero stack pressure and increasing wind speed

Tracer gas testing is a suitable method of taking direct measurements of infiltration rates.

Any increase in liner weight over $50gm^{-2}$ has a negligible effect upon infiltration. The addition of an air impermeable membrane is the major controlling factor. When the liner is used in the field infiltration rates may be almost double those predicted here because of the effects of a flue pipe and a wood or kerosene-burning stove.

The results found fit reasonably to the relationship predicted by a simplified model of airflow, however there are too many unknowns to quantify the area and distribution of openings. The porosity of the tent material needs to be quantified so that the relationship between bulk airflow through cracks and diffusion through the material of the tent can be determined. In this report, the relative proportions were estimated as; diffusion through roof and walls 55%, diffusion through cracks 45%, making a number of assumptions as described in the previous section.

Under realistic conditions, wind driven infiltration is far more significant than the effect of stack pressures. This effect is accentuated by the addition of a liner as stack driven infiltration plateaus at a low level. In still conditions, even if the tent is far warmer than the surroundings, infiltration will not increase significantly. Considering camp planning to minimise wind driven infiltration can be almost as important in reducing infiltration rates as providing an impermeable liner.

The results of this report can be used to estimate infiltration rates in a variety of situations, however more work is required to make them comprehensive.

The $50gm^{-2}$ impermeable liner is the most efficient, in terms of weight and volume, of those tested at reducing infiltration rates and providing a comfortable environment. The low weight and volume of the liner means is easy and cheap to transport and store. This result is backed up by personal experiences in field trials in extreme conditions on a glacier in Switzerland this month. The use of this liner could save up to 8.4kg of wood, or the equivalent, per day in extreme conditions. Current air change rates using this liner, however, are below minimum rates for carbon dioxide accumulation and its use could pose a health hazard. To make the liners habitable a natural ventilation system needs to be designed which can be controlled by occupants to give the required minimum ventilation rate.

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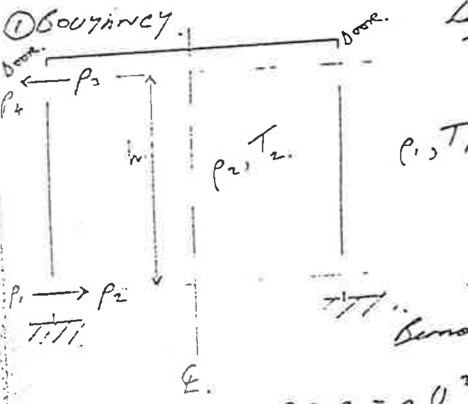
Derivation of Expression for Ventilation.

① BOUYANCY.



longitudinal section through tent.

A C_d for all openings.

Assume gaps at top & bottom of door are the major points of inflow & outflow. - equal height.

Consider flow through only ½ the tent $Q_{tot} = 2Q_v$.

Bernoulli: $p_1 = p_2 + \frac{\rho_1 U_1^2}{2}$.

$p_4 = p_3 - \frac{\rho_2 U_2^2}{2}$.

$U_1 \simeq U_2$ changes in density will create small differences in velocities for equal mass flow rates.

T_2 = average temperature.

$p_1 = p_4 + \rho_1 gh$.

$p_2 = p_3 + \rho_2 gh$.

$$p_1 - p_4 = p_2 - p_3 + \frac{U^2(\rho_1 + \rho_2)}{2}$$

$$\rho_1 gh = \rho_2 gh + U^2 \bar{\rho}$$

$$U = \sqrt{gh\frac{(\rho_1 - \rho_2)}{\bar{\rho}}}$$

$\rho \propto \frac{1}{T}$.

$$\Rightarrow U = \sqrt{gh\frac{(T_2 - T_1)}{\bar{T}}}$$

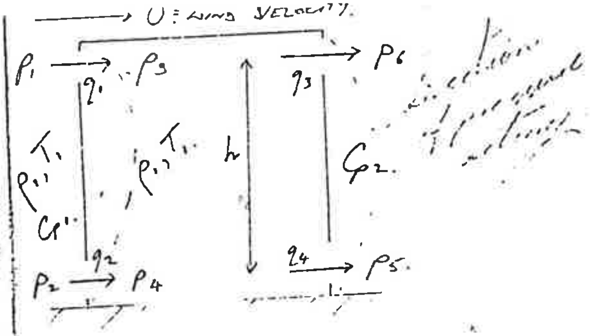
Q_{tot}: Volumetric flow rate

$$= 2C_d A \left(gh\frac{(T_2 - T_1)}{\bar{T}}\right).$$

② WIND DRIVEN INFILTRATION.

$T_1 = T_2$ - disregarding air movement due to thermal bouyancy.

$$Q = C_d A \left(2\Delta P/\rho\right)^{\frac{1}{2}}$$



$$q_1 + q_2 = q_3 + q_4 = Q$$

$p_4 = p_3 + \rho_1 gh$.

$p_2 = p_1 + \rho_1 gh$.

$p_5 = p_6 + \rho_1 gh$.

$$q_1 = C_d A \left(\frac{2(p_1 - p_3)}{\rho_1}\right)^{\frac{1}{2}}$$

$$q_2 = C_d A \left(\frac{2(p_2 - p_4)}{\rho_1}\right)^{\frac{1}{2}}$$

$$q_3 = C_d A \left(2(p_3 - p_6)/\rho_1\right)^{\frac{1}{2}}$$

$$q_4 = C_d A \left(2(p_4 - p_5)/\rho_1\right)^{\frac{1}{2}}$$

$$p_1 = C_{p1}\frac{\rho U^2}{2}$$

$$p_6 = C_{p2}\frac{\rho U^2}{2}.$$

$$q_1 = C_d A \left(\frac{2}{\rho}\left(C_{p1}\frac{\rho U^2}{2} - p_3\right)\right)^{\frac{1}{2}}. \qquad q_2 = C_d A \left(\frac{2}{\rho}\left(C_{p1}\frac{\rho U^2}{2} - p_3\right.\right.$$

$$q_3 = q_4 = C_d A \left(\frac{2}{\rho}\left(p_3 - C_{p2}\frac{\rho U^2}{2}\right)\right)^{\frac{1}{2}}.$$

$$(q_1)^2 + (q_3)^2 = 2Q^2.$$

$$2\cancel{4}(C_d A)^2 \frac{\cancel{2}}{\cancel{\rho}}\left(C_{p1}\frac{\cancel{\rho} U^2}{\cancel{2}} - \cancel{p_3}\right) + 2\cancel{4}(C_d A)^2 \frac{\cancel{2}}{\cancel{\rho}}\left(\cancel{p_3} - C_{p2}\frac{\cancel{\rho} U^2}{\cancel{2}}\right)$$

$$= \cancel{2}Q^2.$$

$$Q = C_d A U \sqrt{2(C_{p1} - C_{p2})}$$