Assessing the Thermal Performance of an Emergency Shelter System

By

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Fourth-year undergraduate project in Group A, 1999/2000

hons (no merit back then)

I hereby declare that, except where specifically indicated, the work submitted herein is my own original work. I also declare that the work I shall submit in the conference style paper is also my own.

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Summary

Two prototypes of a humanitarian relief shelter designed by architects at the Martin Centre, Cambridge University, underwent thermal and condensation performance testing. One prototype used materials proposed in conjunction with Oxfam and the other, composite materials developed by Web Dynamics Ltd.

In the artificial test environment, both shelters experienced undesirable variation of air temperature with height, averaging 17ºC between the lower and middle height zones. The Web Dynamics system performed extremely well in humid conditions with no ice or water developing inside the tent and only very localised dampness on the coldest surfaces. Better seals were achieved with the Web Dynamics design, aiding thermal performance but reducing infiltration and leading to slightly higher relative humidity levels. On the limited time scale of this test, the Web Dynamics system out-performed the other prototype in its response to condensation, as it used breathable membranes to allow water vapour to escape.

Models of each shelter were constructed using the ESP-r simulation package and calibrated with the test data. The shelter models were placed in three different real climates and the figures shown below were derived for annual fuel consumption.

	Web Dynamics Fuel Demand p.a.			Oxfam Fuel Demand p.a.		
	Charcoal	Wood	Kerosene	Charcoal	Wood	Kerosene
Islamabad	1.0m^3	0.9 m^3	0.19 m^3 (190litres)	1.0 m^3	1.0m^3	0.2m3 (200litres)
Kew	7.6 m^3	7.0 m^3	1.5 m^3 (1500litres)	7.6 m^3	7.4 m^3	1.4m3 (1400litres)
Pristina	7.0 m^3	6.8 m^3	1.4 m^3 (1400litres)	7 m^3	6.8 m^3	1.4m3 (1400litres)

The feasibility of heating the tent using only the casual gains from occupants and solar radiation was also investigated. A tent heated in this way would only be appropriate in the Islamabad location as the other sites produced unacceptably low temperatures. Further, with a 1.8kW heat source, occupants in Pristina would need access to an additional 10 togs of personal insulation during the night equivalent to a heavy winter sleeping bag.

Design issues include coping with stratification of air temperature inside the tent, improving light levels without compromising thermal performance and fabricating the materials cheaply and simply.

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1 Introduction

1.1 Background

In the last decade, instability in the Balkans and several high profile natural disasters in Europe and Africa have increased public awareness of the role that governments and aid agencies play in co-ordinating a relief effort. Funding bodies such as the United Nations (UN) and Department For International Development (DfID) are politically accountable and are subject to intense media scrutiny. The aid community has been encouraged to review every crisis so that lessons can be learnt and new strategies established.

One of the key logistical problems which follows a disaster is having to cope with large numbers of displaced people. One aspect of this is the provision of emergency shelter. It is widely recognised that, before resorting to large scale refugee camps, it is preferable to repair existing property or to place refugees with local host families. However, in situations where is too dangerous for people to remain near their homes, temporary shelter may be necessary.

The Kosovo crisis in 1998-9 left many poor, isolated and often inaccessible communities without shelter. In preparation for the region's extremely harsh winter the United Nations High Commission for Refugees (UNHCR) ordered 15,000 winterised tents to be flown in. The shelters were manufactured in Pakistan and took months to fabricate, pack and deliver to the site. By the time the tents arrived many of the Kosovar Albanians had returned home. The UNHCR was left with thousands of useless tents that had to be stored and kept in good condition until they were needed again. The tents cost $11.2 million[1].

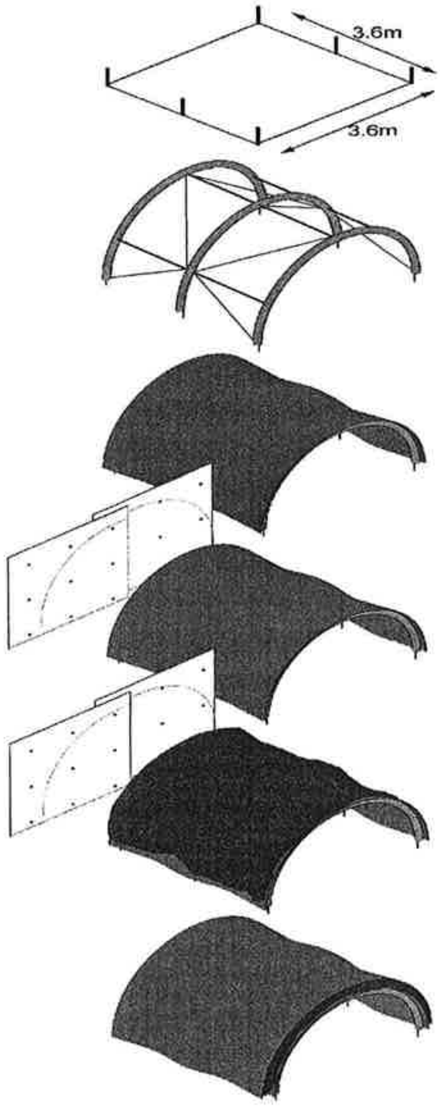
Already, there is a lot of information and documentation about planning refugee camps but very little on setting up suitable temporary accommodation. Factors such as cost, weight, pack volume, delivery time and thermal comfort all come into play. The ability to purchase materials locally has also become important. At the Martin Centre, the research arm of Cambridge University Architecture Department is conducting an investigation into the design of emergency shelter systems. While some testing and analysis of the shelter structure and internal microclimate has already been done, this study aims to collect more information on the problem of condensation inside the shelters at low temperatures. This project will also attempt to develop and calibrate a simulation able to model the shelter in various climates. Useful data from the model will enable estimates to be calculated for the shelter's annual heating requirement and for minimum clothing levels for occupants.

1.2 Existing Shelter Systems and the Design Brief

Thermal comfort is not just a matter of air temperature. It is qualitatively defined as 'that condition of mind in which satisfaction is expressed with the thermal environment'. This state is generally quantified by measuring air temperature, relative humidity and air velocity. While these values can be determined very precisely relating them to the comfort of occupants is terribly subjective. For example it has been found in emergency situations that the satisfaction expressed by refugees with their accommodation depends greatly upon their expectations and the lifestyle they have left behind. Up to a point occupants themselves are able to alter their environment to improve comfort; if conditions are too cold they can don more clothes, pile more fuel onto the stove and block off draughts. The activities that the shelter must support are sometimes unpredictable. Even in camps where centralised washing or recreation facilities are in place, inhabitants may decide to cook, wash clothes, hang belongings up to dry and smoke heavily within their shelters. All these factors affect the atmosphere inside. The design brief is very loose because in emergency situations it is often difficult to achieve a consistent and homogeneous supply of shelter, warm clothing and blankets to refugees. Aid agencies are reluctant to publish minimum standards because they cannot be sure that they will be able to provide the same level of help in every situation.

In developing a prototype, several existing cold climate shelters were looked at by the original researchers[3]. Among these were the standard UNHCR winterised shelter, Scott-type tents used for polar expeditions and a Yurt, an example of vernacular shelter used by nomadic Mongols and Turks. In his 1999 report, Peter Manfield compared the U-values of each shelter, the heat input required and type of clothing used to maintain comfort. The results showed a wide variation in all three values. The polar expedition tent is thin and lightweight but its poor thermal insulation is complemented by the personal insulation of the occupants who use sophisticated and expensive materials such as Goretex™. The Yurt was highly insulated but fairly large in volume so it required an additional heat input from a stove. Finally, the UNHCR shelter fell between the two with an intermediate U-value and a higher required heat input. This helps to demonstrate that in assessing the performance of a shelter system it is important to be aware of the variability of resources available to the occupants. It also suggests that with any new shelter system it is worth investigating the possibility of a zero-rated environment that relies on casual gains from inhabitants rather than extra heaters. In a refugee camp this might be especially useful in reducing the fire risk associated with fuel burning stoves.

Fig 1 Shelter Assembly (Joseph Ashmore, Martin Centre)



The new Martin Centre design is based on the structure shown in Fig 1. The original insulation materials, proposed in conjunction with Oxfam, make up the first prototype. This comprises glass fibre insulation sandwiched by low density polyethylene sheet for the roof and closed cell insulation for the doors and floor. The second prototype uses materials developed in collaboration with Web Dynamics Ltd, a company interested in developing fabrics for humanitarian relief. This composite

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system is made out of wadding with a hydrophilic outer membrane overlaid by a breathable outer sheet. Both systems have been tested.

The UN standards, which are still very vague, suggest an internal comfort temperature of 15-19°C and offer no indication of available clothing (Clo-value), fuel supply or ventilation rates. In addition to the UN standards, it is possible to adopt some of the standards for conventional buildings recommended by the Chartered Institute of Building Services Engineers (CIBSE), although these handbooks refer predominantly to buildings in a UK environment.

1.3 Testing and Modelling Strategy

After discussions with Web Dynamics Ltd, tests were proposed in October 1999 to assess the thermal and condensation performance of the shelter.

The shelter is to be erected inside a cold chamber. Electric heaters will be mounted inside a specially-constructed space heater, which mimics the radiant and convective performance of solid or diesel fuel heaters. Thermocouples are to be used in conjunction with data loggers to give a picture of the thermal performance of the shelter, in static conditions.
Using humidifiers, vapour is to be constantly released into the shelter over a period of time, mimicking habitation and limited cooking and washing. This test will give information about vapour penetration into the shelter fabric and of condensation on the inside surfaces, in static conditions.

It may be helpful at this point to outline the stages of the project in more detail. The experimental results will give an impression of what happens inside the shelter. MSExcel will be used to process and display an overview including a discussion of surface temperatures, air temperatures and relative humidity. Finding an average air temperature can best be achieved using MatLab which can also produce a useful three dimensional graphical display of the changes inside the shelter. The average air temperature will then be used to calibrate the simulation constructed in the ESP-r software package discussed in Sections 3.6-3.8. The unknown variable is the number of air exchanges taking place between external and internal air. In a static environment this exchange is known as buoyancy driven infiltration and is dependent on temperature and pressure differences and the size of holes and cracks in the tent shell.

An air exchange rate can be found by varying the cracks allowing air in and out of the simulated shelter until the temperature inside the model agrees with the temperature recorded during testing. With both temperature and air change calibrated and crack size fixed, the model can then be transplanted from the artificial test environment to several real locations. The output from ESP-r can then give estimates of heat input over the course of a year and information about comfort.

This report outlines the technical background to the experiment and discusses the results both quantitatively and qualitatively. More detailed information can be found in the Appendices and any other results can be obtained from the author.

2 Experiment Design

2.1 Aims

Broadly, the experiment seeks to monitor the behaviour of water vapour inside a cold climate refugee shelter during winter. Changes in temperature directly influence the health and comfort of occupants. Condensation may affect:

- Rate of heat loss, particularly if condensation is interstitial
- Stratification of conditions within the shelter between head height and the sleeping zone
- Ability of occupants to keep their possessions dry
- Mould growth
- Loading on the shelter structure if condensed water freezes on the skin
- Respiratory health of the occupants
- Long term shelter performance

These factors lead to a set of aims.

- To determine rate of heat loss from the shelter and the heat input required to maintain a comfortable temperature inside
- To produce vertical temperature profiles near the heat source and near the door
- To conduct a visual assessment of where condensation collects and how it behaves
- To monitor humidity levels and relate them to comfort and health

2.2 Key Assumptions

The tests were to be carried out at the Novacold depot near Peterborough. The warehouse freezers provided an appropriate ambient temperature and power supply with plenty of space to carry out the tests.

Five key simplifications have been established with the test venue and future modelling in mind.

Assume six occupants. The number of occupants may vary but the testing and modelling assume six people at all times.

Assume constant ambient external temperature of -20°C. This is the lowest design temperature and is considered a worst case for locations such as Kosovo. Outside the ambient air temperature varies throughout the day and diffuse and direct sunlight can change the temperature of the shelter surfaces and internal environment.

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These natural variations have been ignored to limit the number of variables influencing the shelter environment.

Assume maximum moisture content and minimum activity. Most water vapour is generated while the occupants are active. However, moving in and out of the tent aids ventilation and mixing. This activity would counteract the problems of condensation. A simplified worst case would be that maximum moisture content occurs at a time of minimum activity: occupants spend all day being active and generating water vapour up until retiring for the night at which point they are still.

Assume standard values given by CIBSE. The maximum values for moisture content from the CIBSE handbook have been assumed. CIBSE figures for the sensible and latent loads introduced by occupants have also been used. CIBSE information is detailed and readily available but is based on domestic buildings and habits in the UK.

Assume constant rate of evaporation. Different activities at different times of day mean that in reality the water vapour level should vary over a twenty-four hour period. Limitations of the test venue make this difficult to reproduce.

2.3 Producing Water Vapour

The first step is to establish the amount of water vapour that would be produced inside the tent. Using figures provided by CIBSE[4], the following approximations can be made. Table 1 gives figures for vapour produced per hour by 6 people.

Table 1

Source	**Range kg/hr**
Breathing/Perspiring	0.24-0.6
Drying Clothes	0.21-0.58
Total	**0.45-1.18**

Taking the required evaporation rate as 1.18 kg/hr, the maximum value according to our initial assumptions, we can determine the power input needed to produce this rate. There are two steps to evaporating water: the first is to raise its temperature to boiling temperature and the second is to give boiling water an amount of energy known as latent heat, which enables it to evaporate. Equation 1. gives the total energy per second required for evaporation, Q. The first term on the right hand side is the power required to heat 1.18 kilograms of water from the ambient temperature to its boiling temperature and the second term gives the power required to turn boiling water into steam at 1.18 kilograms per hour.

$$Q = mc_w\Delta T + mL \qquad \text{Eq. 1}$$

where

Q is the power input in Watts,

m is the mass flow rate of the water vapour in kg/s (1.18 kg/hr = 3.28×10^{-4} kg/s),

c_w is the specific heat capacity of water (4200 J/kg/K),

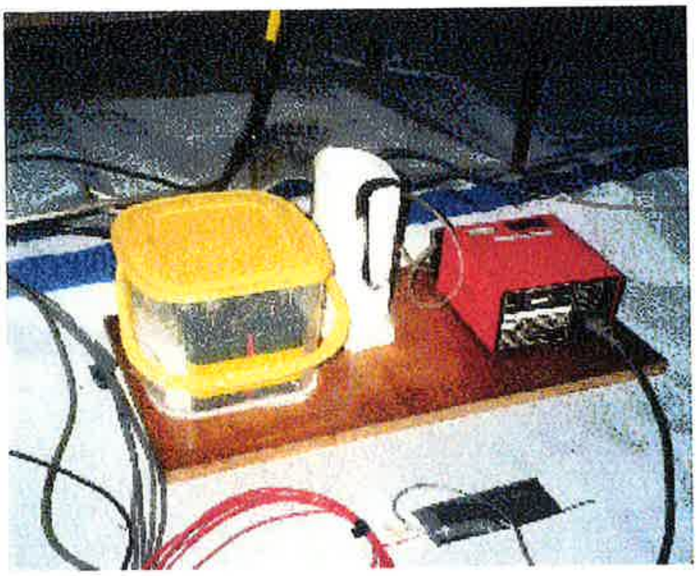
ΔT is the temperature difference (100°C - 15°C = 85°C) and

L is the latent heat of evaporation of water (2.26 MJ/kg).

$$Q = 3.28 \times 10^{-4} \times 4200 \times 85 + 3.28 \times 10^{-4} \times 2.26 \times 10^{6}$$
$$= 858 \text{ Watts (just under 1 kWatt)}$$

After experimenting with several methods of achieving this rate, the simplest solution proved to be a 1kWatt kettle fed by a peristaltic pump calibrated to operate at 1.2 kg/hour. Built into the kettle was a float switch which turned the kettle on as it filled and off when it had boiled off enough water thus it kept pace with the pump and produced the desired level of water vapour. Figure 2 shows a photograph of the set up.

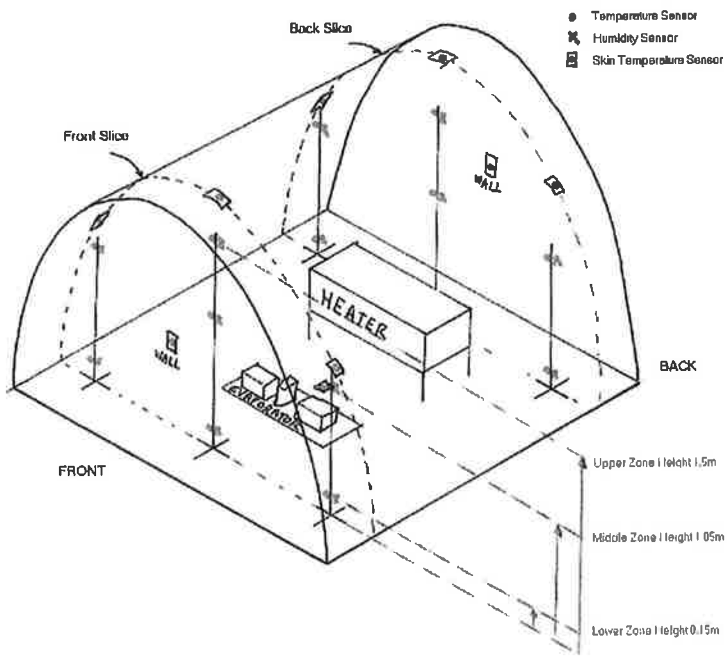
Fig 2 Evaporator



A photograph of the rig equipment.
The pump and kettle set up is designed to model the water vapour produced by people living in the shelter.

The water vapour levels at different points in the shelter were measured by humidity sensors. These were calibrated prior to the experiment and arranged on stands to give a vertical 'slice' through the shelter at the door and at the rear. Figure 3 shows the arrangement of the stands.

Fig 3 Stand Arrangement



2.4 Humidity Sensors and Calibration

Resistive humidity sensors were mounted on 5cm by 5cm individual circuits in series with a 10MΩ resistor. The data logger recorded a potential difference across the transducer in volts dc.

The method of converting this voltage to a useful relative humidity involves placing all the sensors in a sealed environment with a saturated salt solution which regulates the humidity at a known percentage. Table 2 shows the salt solutions employed and the relative humidity values that they reach at equilibrium. The sensors were coiled into a carefully sealed plastic container with the appropriate salt and left to reach steady state over 5 days. Appendix A shows the data used for calibration. The response is linear and these results can be extrapolated to give a conversion factor for each sensor. The sensors are accurate to within ± 5%.

Table 2

Solution	Relative Humidity at 25°C
Potassium Nitrate	92%
Sodium Chloride	76%
Potassium Hydroxide	8%

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2.5 Temperature Sensors

Fig 3 also shows the placement of thermocouples inside the shelter. These sensors were placed to give two vertical slices through the tent including the temperatures of the inside surfaces.

Commercial k-type thermocouples are very accurately calibrated before use but for sound readings the thermocouple 'junctions' must be kept at 0°C. Inside the tent, all the junctions were kept in an insulated container of ice and water to maintain their temperature.

The ambient temperature of the freezer was recorded centrally by the Novacold engineers. This output was provided in graphical form at the end of the testing period.

2.6 Data Logging

A portable data logger was used outside the freezer and connected via leads. It took humidity and temperature readings at 15 minute intervals written to 3.25" low density disk and printed a hard copy of readings taken every 30 minutes.

2.7 U-values and Heat Input

The U-values of the Web Dynamics shelter materials have been worked out and are given in Table 3. Appendix B gives all the additional calculations for U-values and heat input. This value takes into account the thermal resistance of each layer and the thermal resistance of the inner (Rsi) and outer (Rso) surfaces. Rsi and Rso depend on the exposure of the surface and are standard values[4].

Table 3

Surface	**U-value (W/m^2K)**	
	Oxfam	**Web**
Floor	2.26	2.26
Door	1.53	0.98
Wall/Roof	0.28	0.99
Total Conductance (Σ Surface Area x U-value)	**31.99 W/K**	**42.75 W/K**

A lower conductance indicates a better thermal insulator.

Although rated at a combined output of 4.8kW, previous tests[5] have established that in practice the heaters only provide 3.6kW. Two 2-bar heaters placed inside a metal housing were designed to mimic a typical stove.

To achieve a steady state, heat losses must be balanced by heat input. Equation 2 is used to estimate heat losses. It takes account of losses through the layers of insulation (first term) and losses due to the slow exchange of internal air with external air (second term). The tent floor, walls and doors may have different U-values so each surface area is taken in turn and the values for each section of the tent are summed.

$$Q = [\Sigma (A \times U) + V \times n/3600 \times c_{air}] \times \Delta T \qquad \text{Eq.2}$$

where

Q is heat loss in Watts

A is the surface area of the shelter m^2

U is related to the inverse of the tog value W/m^2K

V is the volume of the shelter m^3

n is the number of air changes per hour

c_{air} is the specific heat capacity of air $J/s\ m^3\ K$

ΔT is the temperature difference between the ambient outside temperature and the desired inside temperature

The value of *n* represents the air exchange behaviour. An air change rate will also be taken from the ESP-r simulation after testing but as a first estimate *n* has been taken as 5.5 ac/hr for the Oxfam shelter. This value is based on previous tests carried out by the Martin Centre research team using the Ford Motor Company wind tunnel facility[5]. The same n-value will be assumed for the Web tent.

Eq 2 has been used to work out the heat input required to maintain a steady state internal temperature of 15°C inside the Web shelter.

$$Q = [42.75 + 20.38 \times 5.5/3600 \times 1006] \times [15-(-20)]$$

$$Q = 2550 \text{ Watts}$$

The shelters will experience a heat input from the evaporator of 858W which leaves an additional 1692W to be provided by the heaters. In practice, this must be approximated to the 2-bar output of the heaters: 1800W.

For the Oxfam shelter, assuming the same set up including the heat input from the evaporator and the 2-bar heater, Eq 2 gives a predicted internal temperature of T_i = 22°C for the Oxfam shelter.

CIBSE[4] recommends a comfortable humidity to be 40-70% and a fresh air supply of 17.7 ac/hr for six people in a volume of 20m^3. The minimum ventilation rate for this amount of air space per person is 11.8 ac/hr and if inhabitants are smoking the rate can go up to a maximum of 23.5 ac/hr. The UNHCR suggests a temperature of 15-19°C. These criteria will be the basis of our comfort evaluation.

3 Results and Discussion

3.1 Strategy

Results analysis in this report will move through a general discussion and display of logged data using MSExcel to a more detailed three dimensional scheme using MatLab. In turn the results from MatLab will be used to calibrate the ESP-r model.

3.2 Temperature

The air temperature readings were split into three height zones and the skin temperatures into 4 height zones. Table 4 gives height data.

Table 4

Zone	Type	Height from ground in metres
Floor	Skin	0
Lower	Air Temp	0.15
Middle	Air Temp	1.05
Wall	Skin	1.05
Sides	Skin	1.35
Upper	Air Temp	1.50
Roof	Skin	1.80

The results for each test are presented graphically with the associated values tabulated below.

It is desirable to maintain a fairly uniform vertical temperature distribution otherwise a satisfactory mean temperature may only be achieved by overheating upper zones while the temperature at floor level is uncomfortably low. Ventilation alone cannot reduce large variations in temperature between lower and upper zones. Overheating in the upper layers can be avoided by encouraging air to flow through the tent but this also introduces cold outside air and cools the lower zones still further. Stratification can only be remedied by some kind of mechanical mixing, either by the activity of occupants inside the tent or by using fans. During the night activity inside the tent is minimal, mixing does not take place and stratification is accentuated.

A comfortable maximum temperature will depend on the activity of the occupants but a foreseeable problem may be that people reclining or sitting inside the shelter will occupy the cooler lower zones but also require a higher average air temperature because their physical activity is minimal. Meanwhile, active inhabitants will be on their feet, occupying the warmest parts of the tent and requiring a lower air temperature.

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The skin temperatures become important later in predicting the likelihood of condensation.

The ambient temperature has been taken from data recorded by the Novacold engineers. It varies by ±2°C about an average of -20°C.

3.21 Average temperature by zone

3.212 Oxfam Shelter

Fig 4

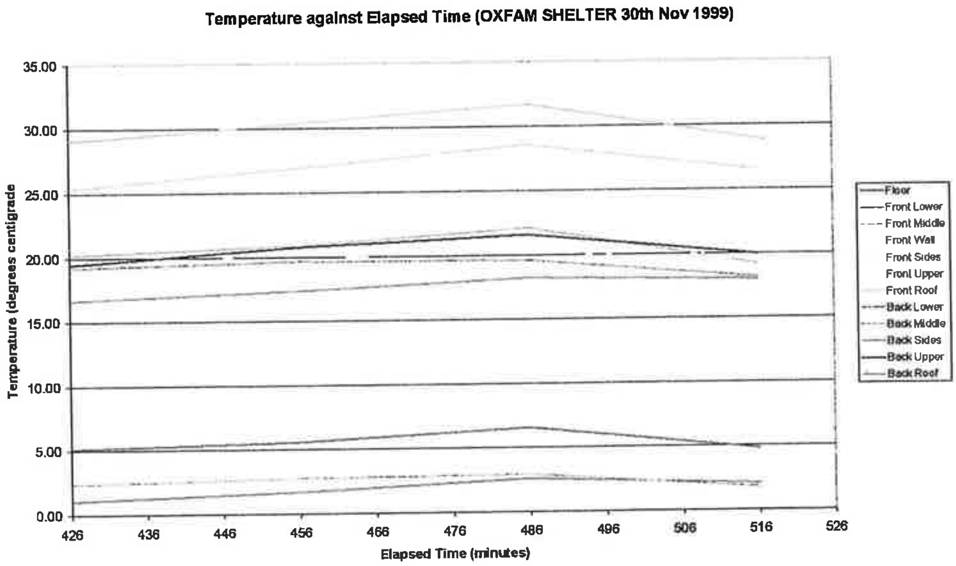

Table 5

Zone	Skin Temperature in °C		Average
	Front	Back	
Floor	5.51		5.51
Wall	19.52		19.52
Sides	19.29	17.54	18.42
Roof	26.84	30.02	28.43

Table 6

Zone	Air Temperature in °C		Average
	Front slice	Back slice	
Lower	1.83	2.44	2.14
Middle	20.57	19.13	19.85
Upper	21.39	20.43	20.91

Between the lower and middle zones the temperature shoots up by 17.7°C over a 90cm height difference. This indicates dramatic stratification of air temperature.

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Except at the lower level, temperatures at the back of the shelter were slightly lower than those recorded through the front slice. This may be because by the door, higher ventilation mixes the air together more thoroughly in the upper zones. More importantly the variation from back to front is only just greater than 1°C.

The sleeping zone is about 2°C which according to research produced for Web Dynamics in 1999[6], would mean additional insulation for sleeping occupants of about 8.4 Togs, for example a winter sleeping bag (10 Togs) or winter clothing (3 Togs) plus a light sleeping bag (5 Togs). 10 togs is equivalent to 1 m^2K/W, the units of thermal resistance.

3.213 Web Dynamics

Fig 5

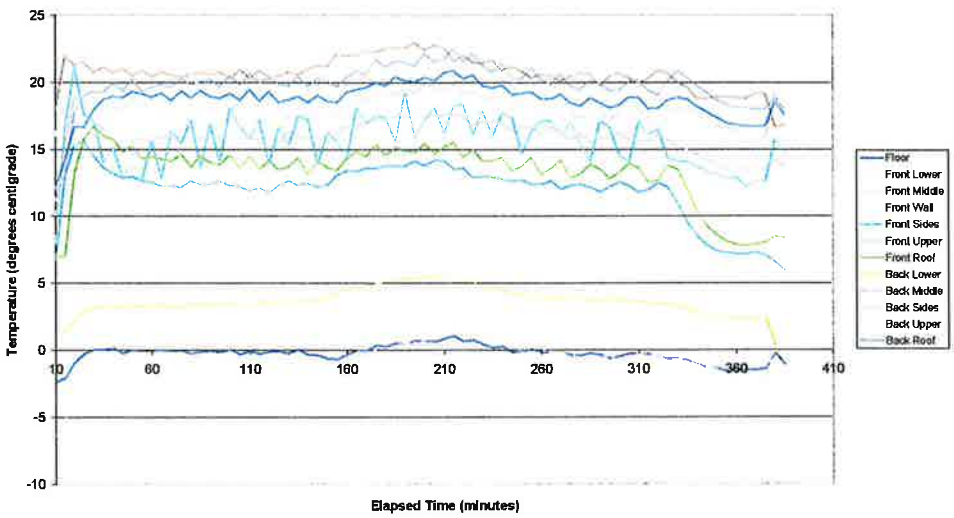


Table 7

Zone	Skin Temperature in °C		Average
	Front slice	Back slice	
Floor	-0.02		-0.02
Wall	17.67		17.67
Sides	12.77	20.39	16.58
Roof	14.23	19.18	16.71

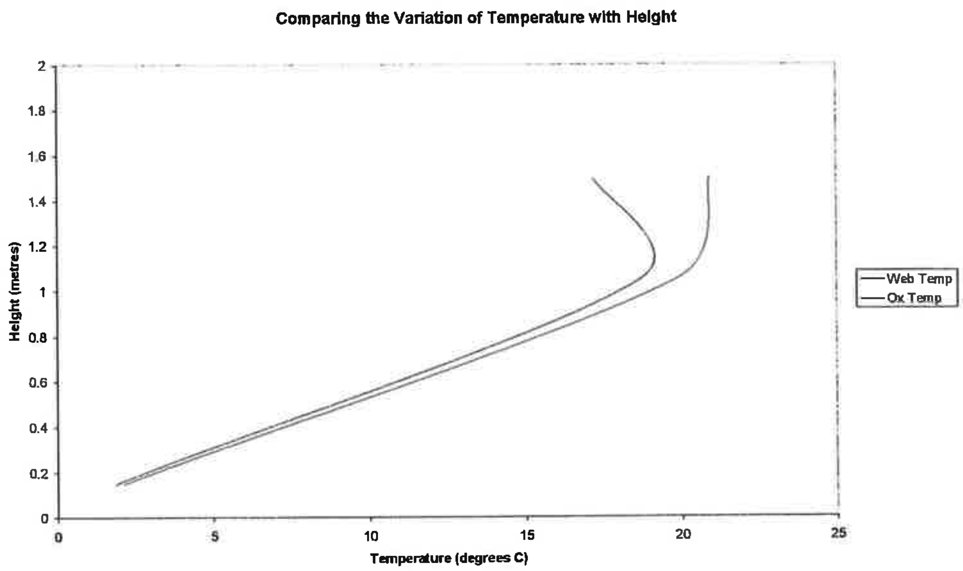
Table 8

Zone	Air Temperature in °C		Average
	Front slice	Back slice	
Lower	-0.24	4.02	1.89
Middle	16.32	21.09	18.71
Upper	16.09	18.28	17.19

The Web Shelter experienced a rise in temperature of 16.8°C between the lower and middle zones. Although this stratification is marginally less than for the other shelter, the middle and upper temperatures are lower on average, though they still exceed the original minimum, mean temperature recommended by the shelter designers of 15°C.

The back of the tent is markedly warmer than the front. The Oxfam shelter used materials produced in separate sections for the roof and the wall. However, the Web Dynamics materials were designed to use just two outer sections; one for the roof and back door, already stitched and sealed, and one for the front door. This created a more effective seal at the back of the tent and kept out rogue drafts. The result is a 4°C difference in middle zone temperatures horizontally through the shelter and a 2°C difference in upper zone temperatures. Vertical stratification is not significantly less than in the Oxfam tent. Fig 6 compares the variation in temperature with height of both shelters.

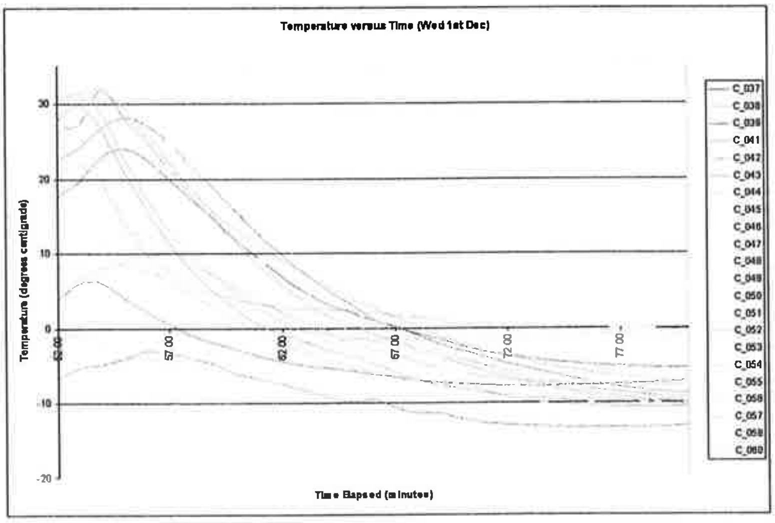
Fig 6



3.22 Removal of the Heat Source

Finally, both shelters have very little capacity for storing heat and Fig 7 shows how rapidly the temperature inside drops without any heat input. This illustrates that after just 15-20 minutes of neglecting the stove during the night, inhabitants will face temperatures well below zero.

Fig 7



3.3 Humidity and Condensation

3.31 Average humidity by zone

3.311 Oxfam Shelter

Fig 8

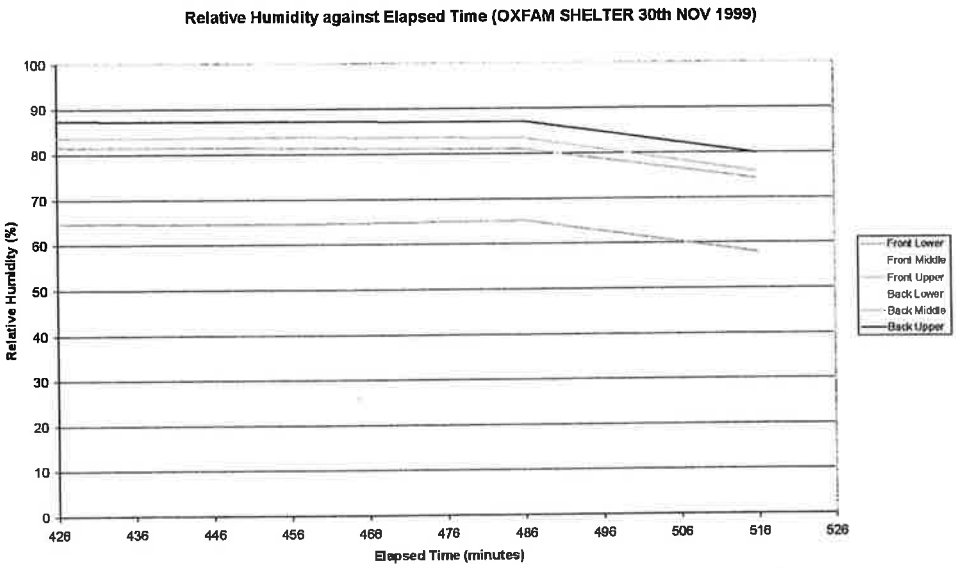


Table 9

Zone	Relative Humidity in %		Average
	Front slice	Back slice	
Lower	79.56	76.35	77.96
Middle	65.39	63.03	64.21
Upper	81.64	85.44	83.54

Variation of humidity with height is much less dramatic than the variation in temperature. The lower and middle zones show a marginally more humid environment at the front of the shelter, possibly because the evaporator is offset towards the front. Relative humidity is greatest in the upper layer.

3.312 Web Dynamics

Fig 9

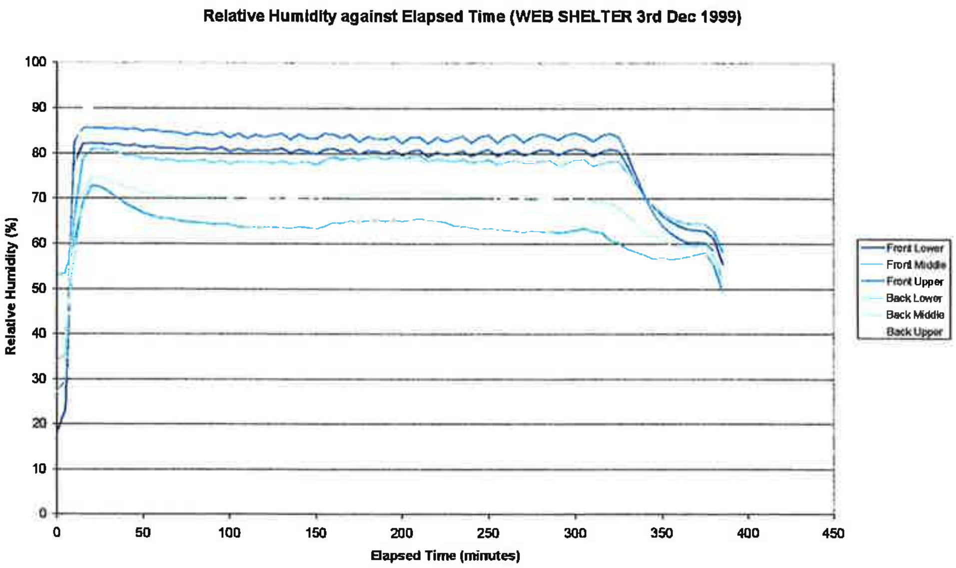


Table 10

Zone	Relative Humidity in %		Average
	Front slice	Back slice	
Lower	80.6	78.4	79.5
Middle	64.4	70.6	67.5
Upper	83.8	86.1	85.0

The middle and upper zones are more humid towards the back of the shelter and average humidity is generally higher than that experienced in the other shelter. Again, this is probably due to lower ventilation rates. The door overlap for the Web Dynamics materials was greater and some seals were pre-stitched, limiting infiltration of air.

In both cases the middle zone has a relative humidity up to 10-20% less than the lower or upper zones. This does not seem to correlate with the temperature gradient through the tent. The explanation for this is not immediately clear. It may be due to pluming effects from the evaporator. For example, steam is produced and rises to the upper zone where it meets the roof and spreads like a mushroom cloud, dropping down to the lower zone where it sits and collects, leaving the middle zone less humid. Alternatively the distribution of water vapour could be reflecting the pattern of air movement through the shelter. Perhaps air enters through the door at mid-height and escapes through the seals at floor level and in the roof, encouraging steam to be drawn down or up. The reverse of this is also a possibility; humid air allowed to escape through the door at mid-height. Whatever the true explanation, with sensors accurate to ±5%, the variation is too small to make any meaningful conclusions about humidity distribution.

3.32 Skin Temperature and Condensation Rate

Two forms of condensation have importance in construction. Surface condensation, the development of moisture on a surface, becomes problematic if mould can form or if moisture collects and runs or drips onto blankets, clothing or the occupants themselves. Interstitial condensation occurs when moisture condenses within the insulation materials. Over time this can reduce the efficacy the insulation.

Condensation takes place when the temperature of a surface falls below the local 'dew point', a value dependent on the particular temperature and pressure of nearby water vapour. From the values of local air temperature and local humidity, it is possible to establish a 'dew point' and then to predict whether condensation is possible. Published data, presented as psychrometric charts[4], are available to relate temperature, humidity and 'dew point'.

The tables held in Appendix C have been worked out from psychrometric charts and they give an approximate prediction of where condensation will first occur. Although skin temperature does not fall below the corresponding 'dew point' in any of the zones, it can be seen that the values converge at the front of the tent. This is at odds with the visual assessment for two reasons. Firstly, in practice, condensation occurs partly because of the effects of cold bridges which have a much lower resistance to the passage of heat and consequently a lower surface temperature. In this shelter it is the metal purlins and metal base pegs that act as bridges. The cold surfaces at lower levels create a distinct pattern of condensation, illustrated by the visual assessment. Secondly, the measurements of local humidity and temperature may not have been recorded close enough to the surface in question.

The rate of condensation in kg/m^2s is proportional to h_m, the surface mass transfer coefficient. The key point regarding this coefficient is that it depends on the

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direction of heat flow through a surface with respect to gravity. For surfaces with the same local humidity, local air temperature and skin temperature, more water will condense on the surface that has heat flow upwards or horizontally than a surface with heat flowing downwards. For example, at floor level the walls and sides will accumulate more water than the floor. Again this is confirmed by the visual assessment and also compounds the problem of predicting condensation as this is not only dependent on height, temperature and humidity but also on the angle of inclination of the surface.

3.4 Visual Assessment

3.41 Oxfam

Ice formed where condensation had run down the inside walls of the tent and frozen around the cold bottom edges. This problem was particularly acute around the door flaps and corners where ice build-up could be seen up to 30 cm above the floor. Ice formed on the poles up to a height of 40 cm, approximately the height of the base pegs. These metal pegs act as cold bridges inside the plastic poles. Water droplets collected on the top purlin and dripped back into the tent. Ponding could be seen on the floor beneath the back flap. The driest areas were at roof level in the middle of the shelter. The shiny plastic texture of the door flaps meant water streamed down the panels and froze in icicles and rivulets at ground level while the rougher surfaces of the tent sides held the condensation and spread it in a more even layer across the sheet. Figs 10-12 show schematic sketches of the distribution of frost and ice on the interior walls.

Fig 10 Front Door

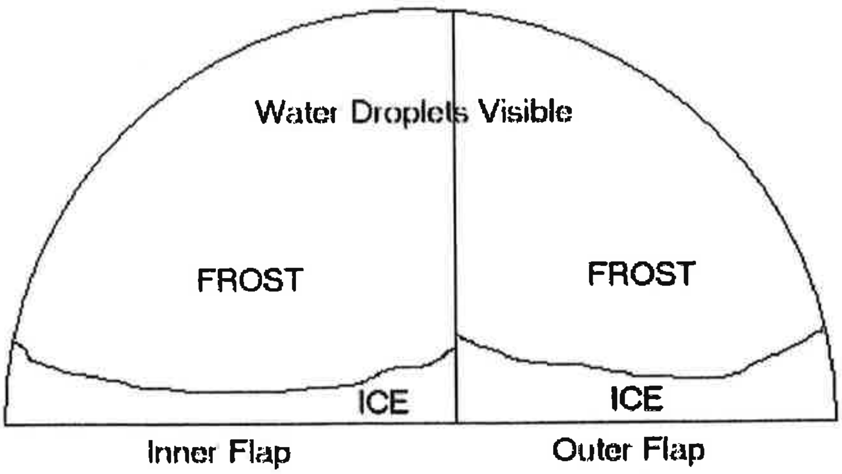
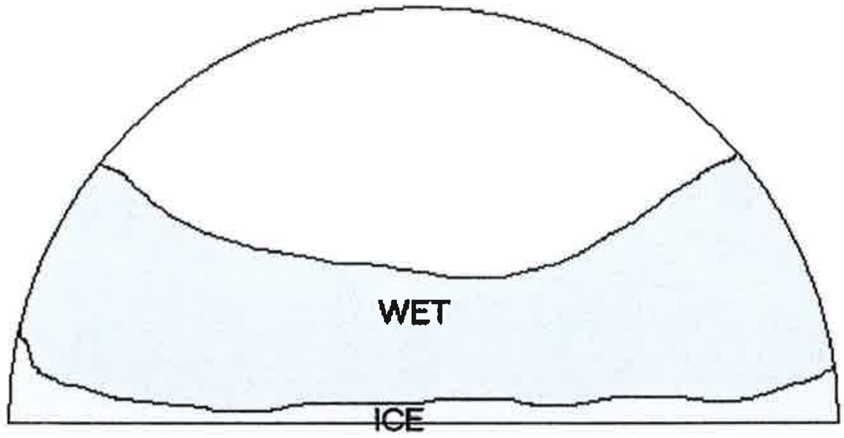
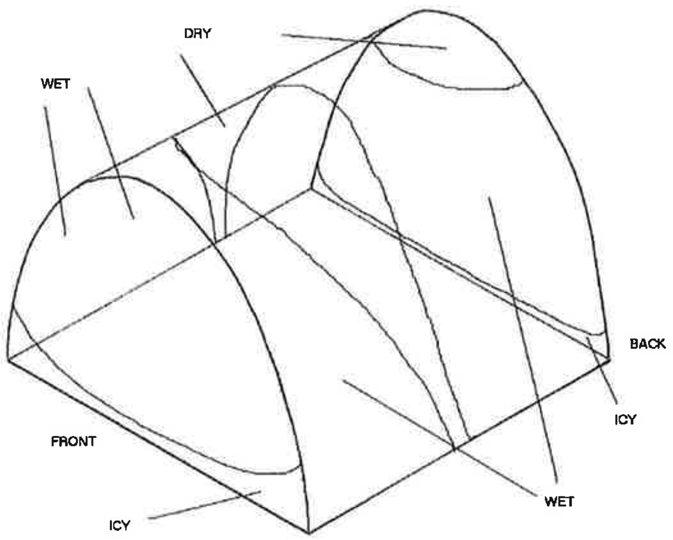


Fig 11 Back Door



Back Panel

Fig 12 Patterns on inside walls



3.42 Web Dynamics

Fig 13 Shelter Set Up

Assembling the shelter with representatives from Web Dynamics and Cambridge University Engineering Department.

No ice formed inside the tent. In the coldest zones, up to half a metre above ground level, the materials were slightly damp but because of their texture the water was not collecting and dripping, instead being absorbed and held. These damp patches, sketched in Fig 14, caused slight sags in the wadding.

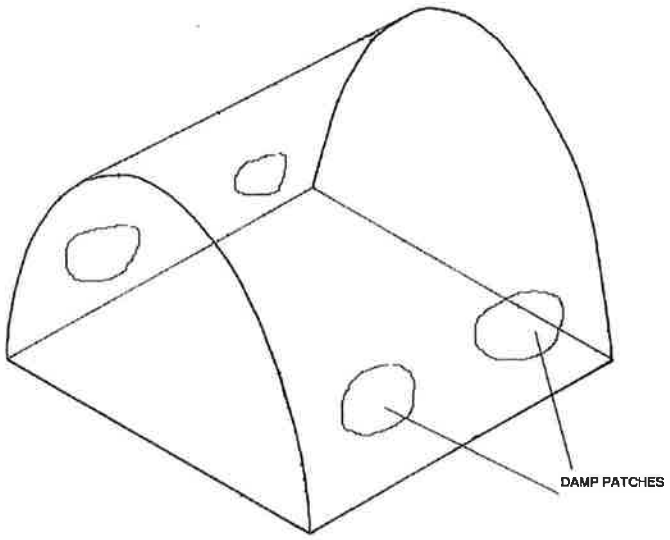


Fig 14

As hoped the material was allowing water vapour to breathe through the first layer and hit the water proof outer membrane. Here, temperatures were low enough to freeze the condensation. The inside surface of the outer membrane was frosted and an icy layer was building up. The inside layer with its breathable outer surface also began to frost as water became trapped and frozen in the wadding.

The door flaps gave a good picture of the routes that water vapour could take. Fig 15 shows the pattern that developed on the inside surface of the dark blue outer layer. In the coldest zone, up to 30 cm above floor level, no frosting or moisture was visible on the surface of the blue fabric. Instead, the water vapour escaping at this height was freezing in the wadding before it had passed through to meet the outer sheet.

Above this 30cm cut off height, surface frosting and frozen rivulets of water were seen. At this level it was warm enough for the water vapour to pass through the wadding and collect beyond the breathable membrane on the inside of the blue outer sheet. Any interstitial water vapour condensing in the wadding did not freeze at this level.

Between 60 and 130 cm above floor height, frosting did not occur in the wadding or on the blue outer sheeting though moisture had condensed.

Above 130cm, the inside of the blue surface was dry again. This time not because the cold temperatures trapped frozen water vapour in the wadding but because warmer temperatures allowed the water vapour to escape altogether. This emphasises the importance of keeping the tent warm in order to purge water vapour before it condenses on or inside the shelter skin.

Fig 15

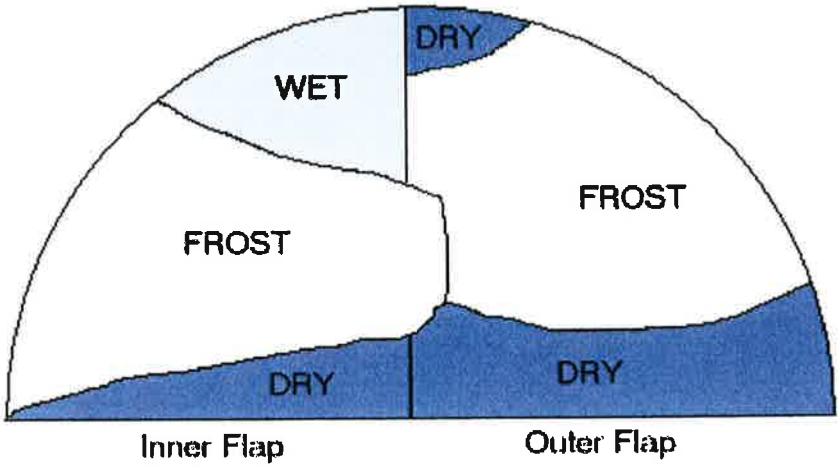


Fig 16 A Series of Photographs Showing Frosting on Panels

This phtograph shows the development of frost between the inner and outer insulation layers. This is the back panel with the highlighted area about 1.5m above the ground.

This photgraph shows the development of frost between the door flap and the insulation.

This photgraph shows the development of frost on the door flap.

3.5 Heat Losses

Initially, Eq. 2 was used to work out a steady state mean temperature for a particular heat input. Stratification makes it difficult to evaluate a mean temperature across the zones. A crude evaluation can be achieved by multiplying each zone's temperature by the zone volume (approximated by three horizontal slices), adding up these values and then dividing by the total volume.

Table 11

Zone	Volume Slice, V (m3)	Web Dynamics		Oxfam	
		Temp, T (°C)	T x V	Temp, T (°C)	T x V
Lower	8.1	1.89	15.3	2.14	17.3
Middle	7.7	18.71	144.1	19.85	152.9
Upper	4.6	17.19	79.8	20.91	97.1
Total	20.4		239.2 °Cm^3		267.2 °Cm^3
Total/Total Volume			**11.7 °C**		**13.1 °C**
Predicted Temp			**15°C**		**22.0 °C**

As predicted by Eq 2, the Oxfam shelter gives a higher mean value than the Web Dynamics shelter for the same heat input. However, both shelters are under-performing and not reaching the predicted mean temperature.

This temperature-by-volume estimate can be refined by using MatLab to interpolate the results and then calculate an estimated temperature-by-area for a large but finite number of points inside the shelter. Fig 17 shows the graphical output from

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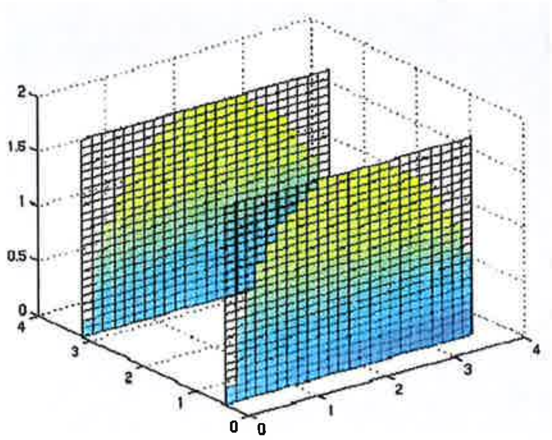
MatLab: a 'frame' from the 'movie' of results. Fig 17 has been created to give a picture of the internal environment but the data between the floor and the sensors at 0.15m and that between the sensors at 1.5m and the roof is actually unknown. Extrapolation right to the edges of the tent has been achieved by repeating the lowest and highest horizontal data slices at floor and roof level and then interpolating. Appendix E holds extracts of the MatLab code and results.

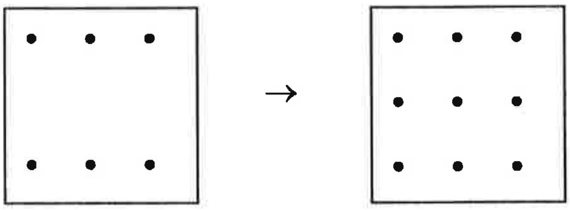
In fact reliable linear interpolation can only be carried out for a cuboid space inside the shelter limited by the sensor positions. Each element of the grid generated by MatLab has an area of 0.15 x 0.75 m^2 and an assigned temperature either from the results database or from the interpolation executed by MatLab. Each element of the temperature matrix is multiplied by the element area and then divided by the total area to give an average temperature for the front and back slice. An average of these is then taken and used to calibrate the model.

Fig 17



Problems with the accuracy of this method come from two main sources: interpolating between a limited number of data points and interpolating linearly. MatLab requires an evenly spaced grid of data in order to interpolate. The experiment produced a set of points with the pattern shown in plan in Fig 18. To produce a grid of 3 by 3 data points, an additional set of data was inserted into the data matrix. This was the mean average of the front and rear slices.

Fig 18



This liberty with the data does not significantly compromise the accuracy because the mid point between two data points in a linear interpolation will indeed be the mean average. A difficulty may arise because the interpolation is through the volume not just between two points but this leads on to the more significant problem of using a linear relationship.

Temperature variation with height is dependent on convective heat flow which is not necessarily linear. This linear approximation is carefully justified Section 3.7.

Returning to Eq. 2, we can use our refined mean temperature approximation to work out a new estimate for number of air changes:

Table 12

	Web Dynamics	**Oxfam**
Temp from MatLab	9.5 ºC	11 ºC
Predicted Temp	15 ºC	22 ºC
Air changes per hour (ac/hr)	8.3	9.4

Table 12 confirms that it is heat loss through infiltration which accounts for the discrepancy between predicted and measured temperatures. The air change rate which was the uncertain variable at the out set has now been fixed more accurately. This calculation also suggests heat loss due to infiltration is slightly greater from the Oxfam shelter.

3.6 ESP-r Modelling

The Environmental Systems Performance – research tool, developed at the University of Strathclyde, has been used to simulate the energy and fluid flows inside the shelter.

The theoretical basis of this software is three-fold. First, it takes the standard Fourier Heat Flow Equation to model all heat flow paths through the boundaries between zones. Secondly, a finite difference method is used to solve the Fourier Equation numerically for each finite volume. Thirdly, the package demands mass balance, an overall agreement between mass flow entering and leaving each element. User defined nodes represent perfectly mixed fluid volumes. Fluid to fluid exchange between nodes is due to pressure, temperature or mechanical effects. Fluid to surface exchange is a result of local convective effects.

There are three steps in the development of a suitable model: construction and calibration using artificial climate data, followed by adaptation with real climate data.

3.61 Artificial Climate

3.611 Construction Materials

The two ESP-r databases which hold the descriptions and properties of all kinds of building materials have been updated to include the Oxfam and Web Dynamics materials and their composite arrangements. The emissivities of all the shelter materials have been reduced to just 0.01 because in the artificial environment there is no direct or diffuse sunlight and the heat gains through long wave radiation passing through the walls of the shelter must be neglected and left uncalculated. With such low emissivities, ESP-r will be able to ignore these tiny false heat gains.

3.312 Climate Data

ESP-r climate files include data on diffuse horizontal solar radiation, direct normal solar radiation, air temperature, relative humidity, wind speed and wind direction. Air temperature is fixed at –20°C for the artificial climate and relative humidity at this low air temperature is 100%. All other data sets are zero as the shelter is in totally still conditions with no sunlight.

3.313 Zone Structure and Control

For the artificial climate we require two zones. The first is that of the tent itself which is constructed from surfaces with the relevant material attributes. ESP does not model moisture release into the tent so deciding on an appropriate control function to model heat input alone is not straight forward. The power provided by the kettle does not all go to heat the tent. The kettle contribution has been split into a non-evaporative (144W) and evaporative component (714W). The control function has been modelled as a constant fixed heat injection of 1800W (heater) plus 144W (kettle). The evaporative contribution appears as a latent load of 714W representing the heat input able to support evaporation and water vapour produced by six occupants.

The floor of the shelter is in contact with the concrete floor of the freezer. This lump of concrete has a large mass and a high specific heat capacity so its temperature is not affected by changes in the temperature of the tent. Although ESP-r gives a variety of options for the behaviour of the outside surface of the floor, none would behave as the concrete behaves in this test situation. Thus a second zone to mimic the concrete floor must be constructed. This is simply a block with thick concrete surfaces and an internal control function that keeps the core temperature of the concrete at -24°C and its outer surface temperature at -20°C. Fig 19 shows the final model in the ESP-r project manager.

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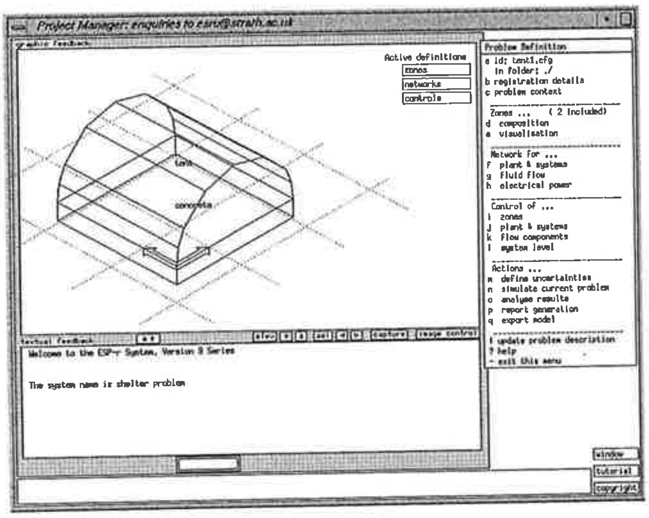
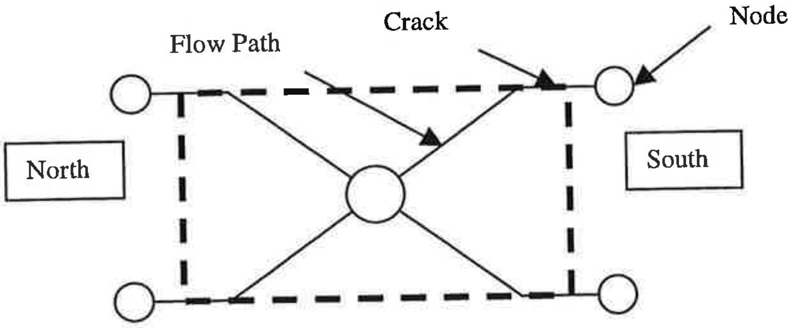
Fig 19



3.614 Calibration and Fluid Flow Network

In conjunction with the network of energy flows through the surfaces, ESP-r sets up a network to model fluid flow in and out of a zone. The shelter is not perfectly sealed and this model uses idealised cracks to allow leakage and air exchange to take place. The network consists of five nodes: the first sits at mid height inside the shelter and represents the shelter volume. The other four are connected to this node via cracks at the top and bottom of the door panels. Fig 20 shows the node positions in a cross section in elevation through the tent.

Fig 20



The connection characteristic is a crack with variable area and discharge coefficient. The network has been kept as simple as possible and the justification for introducing four external nodes is that the network must represent buoyancy driven infiltration. While this does not require pressure and temperature stratification inside the tent (thus only one internal node), it does require flow paths which allow exchange between the external and internal environments. Once air has entered the tent and warmed up it must have a flow path out again. For symmetry both ends of the tent

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allow flow in and flow out. The positioning of cracks at ground level and roof level represents the worst leakage along the seams of the real tent.

To calibrate the model in the artificial climate, the crack areas are varied until the temperature at the inside node is equal to the average steady state air temperature computed by MatLab. Agreement of 0.5° is achieved. The correct crack area is fixed and the air change rate is recorded for the shelter in static conditions at an ambient temperature of -20°C.

Table 13 gives the air change rates produced by the simulation. Clearly, the results differ considerably even though, for the static artificial conditions, ESP-r will be using a form of the Fourier equation exactly like Eq 2. Section 3.7 seeks to explain this result.

Table 13

	Web Dynamics	**Oxfam**
Air changes per hour (ac/hr) from real test	8.3	9.4
Air changes per hour (ac/hr) from model	6.3	6.5

3.62 Real Climate

3.621 Construction Materials

The only difference in the materials for use in the real climate is that they must pass solar radiation. The emissivity values are returned to numbers appropriate to the material.

3.622 Climate Data

The program MeteoNorm is used to compile climate data from different regions. These ASCII climate files are converted in to a binary format by ESP-r and site data including longitude and latitude are read in. Climate files for Kew, UK (default), Pristina, Kosovo and Islamabad, Pakistan have been used.

3.623 Zone Structure and Control

In a real situation the concrete block must be removed and replaced with the standard 'Ground' option supported by ESP-r. This takes the monthly profile for February as the yearly ground temperature.

The control options depend on the results required. For both types of shelter two control conditions have been designed. The first assumes a heat input derived only from the occupants. The control function is free floating and the occupants are represented by a sensible load of 600W and latent load of 90W equivalent to that generated by 6 inhabitants[4]. The second assumes a fixed heat injection of 1800W actuated by a temperature drop below 15°C and switched off once the temperature reaches 19°C.

3.7 Integrity of the Model

Any output from the ESP-r model is useful only if the user has confidence in its accuracy. Three crucial factors must be addressed in discussing the validity of the shelter model:

- Computational errors resulting from the numerical methods used by ESP-r
- Simplification of the mass flow network
- Accuracy of the calibration data

Any truncation errors that come about when ESP-r computes are insignificant compared to the level of uncertainty surrounding the nature and behaviour of the cracks built into the model.

The mass flow network is defined by nodes and connections. The connections or cracks are represented by an area and a discharge coefficient, Cd. The low value of Cd used by the model is not based on any empirical evidence but has been imposed to ensure that crack area becomes the dominant characteristic of the orifice rather than the shape or edge effects. It is in each end panel that the real shelter has most of its fabric joints and leaks so it is here that the idealised cracks have been placed in the model.

The calibration data has been taken from MatLab's temperature-by-area calculation which interpolates linearly between temperatures in the horizontal plane and then in the vertical plane. In fact, the changes in internal air temperature vary non-linearly in both directions: in the horizontal plane because of the heat input centred around the stove and vertically because of convective effects which introduce a non-linear stratification.

This method can be justified first by looking at ESP-r. This software assumes the tent volume to be single zone with approximately equal and symmetrical physical dimensions[7]. It takes only a simple account of the fluid exchange and no detailed account of the fluid dynamics because it is not a CFD model; already the programme itself makes an approximation when computing zone temperature. These tests have not been to analyse the internal microclimate in detail, instead they have been used to give a general picture of comfort zones and to estimate the running costs and look at the habitability of the shelter. Shelters assembled in the field will vary depending on how well they have been built and how well equipped their occupants are. This

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uncertainty outweighs the errors accrued by approximating the temperature data to a linear interpolation.

The air change rates computed by ESP-r in the artificial climate are lower than those calculated manually for the actual test. This can be accounted for by the fact that, in the test situation, the air inside the shelter held high quantities of water vapour. This mixture of gases may have changed the pressure and temperature characteristics of the tent more than the evaporative latent load used by the model. The breathable Web Dynamics material would have allowed water vapour to escape whereas a higher pressure might be expected within the more impermeable Oxfam shelter. A higher internal pressure would lead to more buoyancy driven infiltration and a higher air change rate. This flaw with calibrating the model can only be resolved by further testing without the presence of water vapour.

3.8 Results

3.81Climate Summary

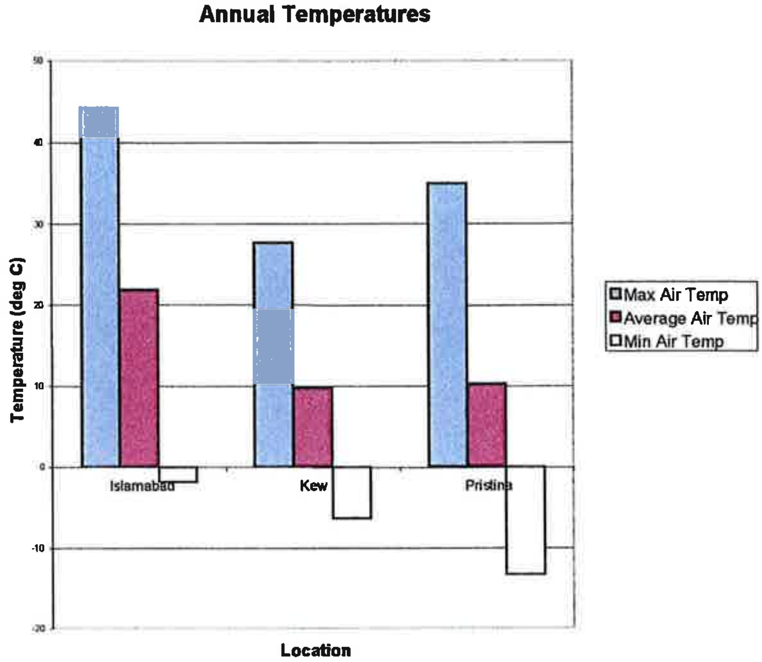
Table 14

	Islamabad	Kew	Pristina
RH (%)	57	77	69
Wind Speed (m/s)	1.3	3.9	3.2
Wind Direction (degrees from N)	139	190	21
Diffuse Horiz Solar Radiation (W/m2)	509	265	482
Direct Normal Solar Radiation (W/m2)	996	833	973

Table 14 summarises the climate data showing average annual values. Kew experiences the strongest wind, the highest humidity and the least solar radiation. Islamabad is exposed to the most solar radiation, the weakest wind and the lowest humidity. Pristina is similar to Kew but has higher annual solar radiation. Kew is the default location used by ESP-r and it has been included as a useful comparison but not as a potential location for siting the tents.

Fig 21 shows that Islamabad has the highest annual average temperature, the highest maximum temperature and the highest minimum temperature. Pristina has the lowest minimum temperature.

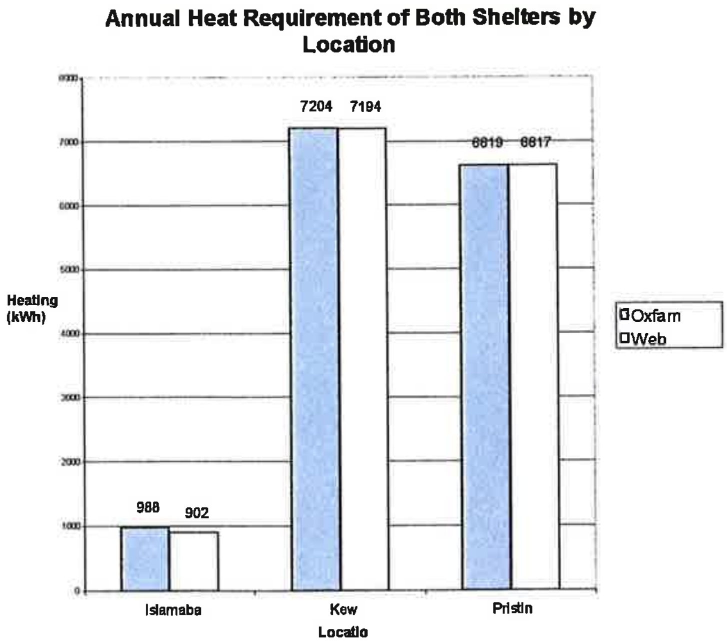
Fig 21



3.82 Heat Gains and Losses

As illustrated by Fig 22, both shelters have very similar heating requirements over the course of a year. Kew requires the greatest annual heat input because of its high wind speeds and low solar gains. Pristina experiences solar gains but these are outweighed by the very low winter temperatures.

Fig 22



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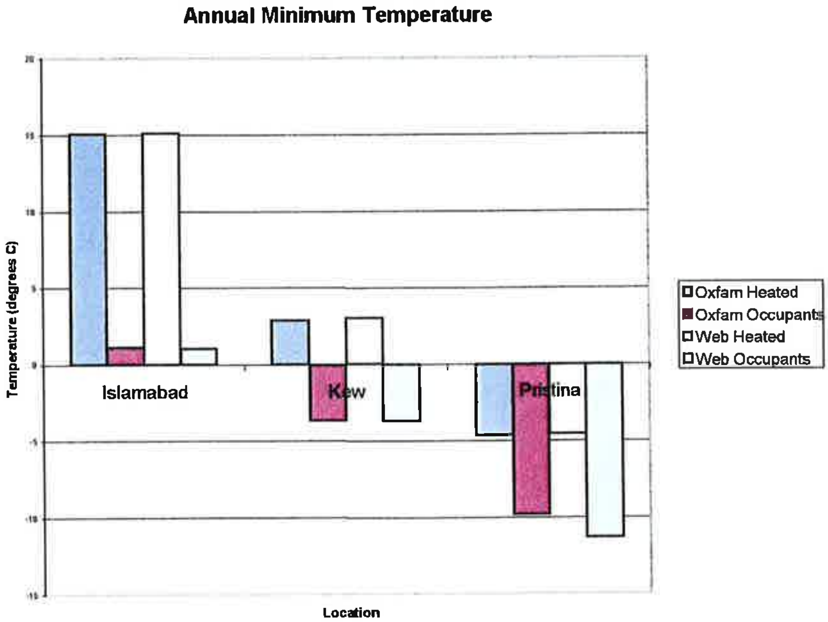
3.82 Internal Environment

3.821 Temperature

Fig 23 shows the minimum annual temperature inside each shelter. Only in Islamabad is it possible to prevent the temperature falling below 15°C just by using a 1.8kW heat source. In Pristina, even with a stove the temperature inside the shelter can drop to a minimum of -4°C. At this temperature according to research produced for Web Dynamics in 1999[6], inhabitants would need additional insulation of about 10 Togs. Aid agencies would have to be able to supply winter sleeping bags (10 Togs). Winter clothing (3 Togs) and light sleeping bag (5 Togs) may not be enough to prevent cooling during the night.

Fig 23

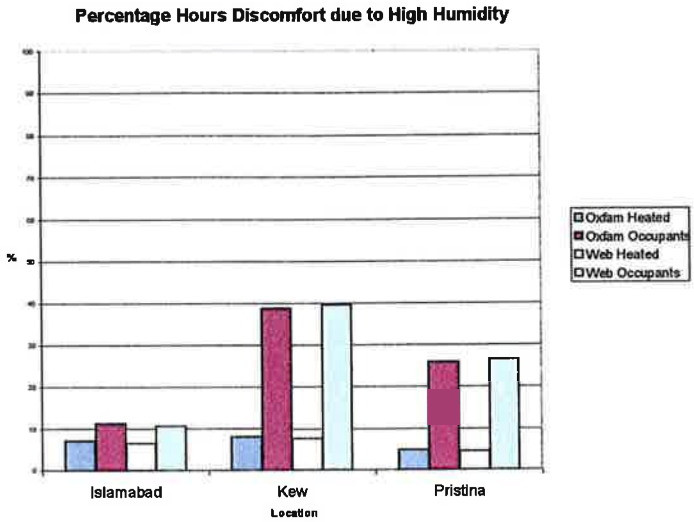


The unheated Web Dynamics tent experiences a minimum average temperature of -12°C about 2.5°C than inside the Oxfam tent. At these low temperatures, about 12.5 togs of extra insulation is needed. This is unacceptably cold and enough clothing and blankets to meet this requirement would restrict people's mobility and increase discomfort.

3.822 Humidity

The humidity results from the model are based on the combination of ambient climatic humidity and the latent load inside the shelter and are not derived directly from the production of water vapour by occupants.

Fig 24

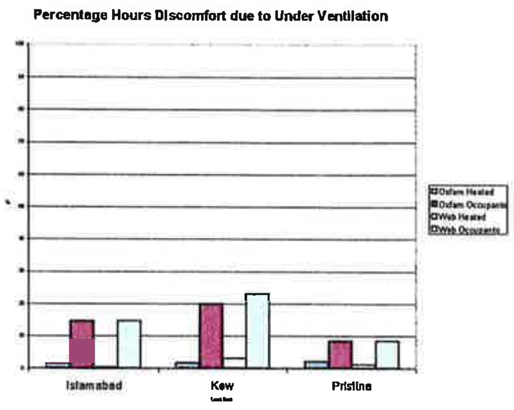


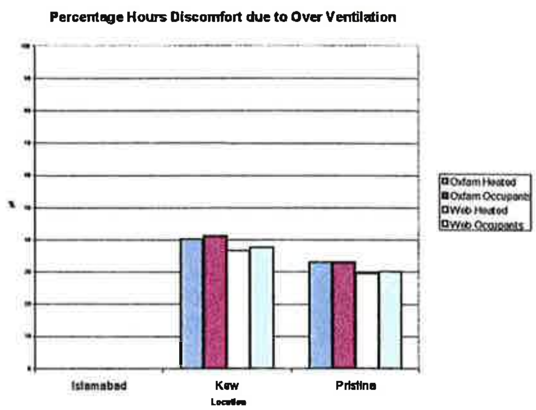
In Fig 24, we can see that the greatest problems with high humidity occur in the unheated tents. This mirrors the problem of under ventilation illustrated in Fig 25 below. Poor quality humid air is more difficult to purge if the space is under-ventilated. Relative humidity is a measure of the quantity of water contained in air expressed as a percentage of the maximum which could be held by the air at that temperature and so psychrometric charts[4] show that for the same mass of water held in dry air, the relative humidity falls as temperature rises. As far as comfortable humidity is concerned, the heated shelters have the advantage.

3.823 Air Change Rate

Figs 25 and 26 show the percentage of uncomfortable hours due to under or over ventilation. Where the ventilation rate falls below the recommended minimum of 11.8 ac/hr but the air temperature is above 15°C, it has been assumed that occupants will take action to ventilate the tent themselves. When this condition applies the shelter has been assumed comfortable. Under ventilation is more acute in the unheated shelter, highlighting the importance of encouraging buoyancy driven ventilation by heating the shelter. Over ventilation is the dominant problem in Pristina with uncomfortable draughts for 30-35% of the year. The Oxfam shelter performs slightly worse than the Web Dynamics shelter due to its higher leakage and larger crack sizes. Orientation is also a factor affecting wind driven infiltration for the shelters oriented with the North to South flow network parallel to the prevailing wind direction. From Table 13, the prevailing winds at Kew and Pristina are 10° and 21° out of North-South alignment while in Islamabad this figure is 41°. Combined with the lower wind speed at Islamabad this explains why the shelter in this part of Pakistan does not suffer from over-ventilation.

Figs 25 and 26

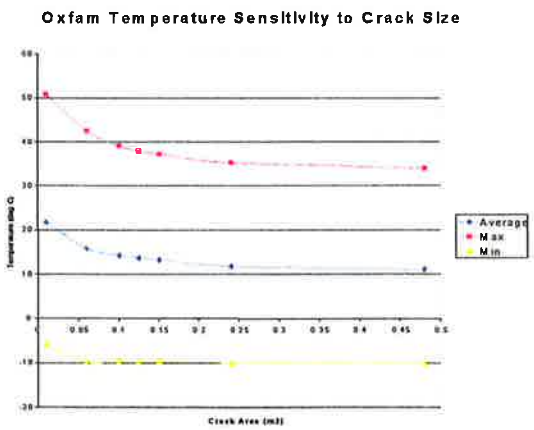


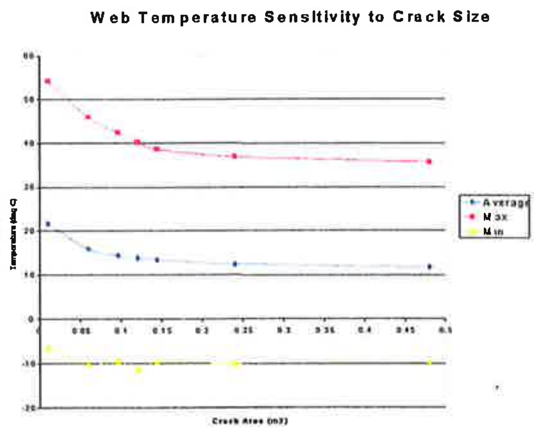


3.83 Sensitivity

Finally, for a brief look at the temperature sensitivity of the model to a change in crack area, the unheated shelters have been placed in Pristina and analysed with different crack areas. For calibration the crack area was fixed at 0.125 m^2 for the Oxfam model and 0.12 m^2 for the Web model, this is about 2% of the total door area. Figs 27 and 28 show that the relationship is extremely non-linear and that it is the maximum annual temperatures that are most affected by changes in crack size. We are more concerned with low temperature behaviour where, unless crack size is reduced to below 1% of the door area, temperatures are hardly affected. If occupants are able to block leaks and draughts it may be possible to raise the lowest temperatures by 5°C but only at the cost of lower ventilation rates. Once greater than 0.5-1.0 m^2, a crack will no longer behave like an orifice and a different type of connection should be used between the nodes.

Figs 27 and 28





In field conditions both the variation in the quality of assembly and the behaviour of occupants are uncertain. Having seen both shelters set up, I suspect that in the field the Oxfam shelter would be subject to greater variability in construction because its separate sections make erection more complicated and time consuming.

4 Conclusions and Recommendations

4.1 Thermal Performance

4.11 Heating and Comfort

Testing the shelter in still conditions allows us to estimate the buoyancy driven infiltration and leakage associated with this structure. Once leakage characteristics have been modelled, ESP-r works out the heat losses derived from wind driven infiltration in a real climate. Table 15 looks at a summary of fuel demand for each shelter based on the ESP-r power consumption and the calculations in Appendix D[8]. Stove efficiency at 65% has been assumed.

Table 15

	Web Dynamics Fuel Demand p.a.			Oxfam Fuel Demand p.a.		
	Charcoal	Wood	Kerosene	Charcoal	Wood	Kerosene
Islamabad	1.0m^3	0.9 m^3	0.19 m^3 (190litres)	1.0 m^3	1.0m^3	0.2m3 (200litres)
Kew	7.6 m^3	7.0 m^3	1.5 m^3 (1500litres)	7.6 m^3	7.4 m^3	1.4m3 (1400litres)
Pristina	7.0 m^3	6.8 m^3	1.4 m^3 (1400litres)	7 m^3	6.8 m^3	1.4m3 (1400litres)

Although a shelter which relies on casual thermal gains to achieve comfort has advantages in cheaper running costs and a reduced fire risk, a colder shelter is not able to promote the ventilation necessary for comfort. Without a significant temperature difference between inside and outside, infiltration remains low and, without a reliable supply of personal insulation for the occupants, a zero-rated shelter is inadequate to keep people warm over night.

Even with its higher conductance, the pre-stitched seams of the Web Dynamics shelter are enough to put the shelter on a par with that of Oxfam as far as comfort and fuel demand are concerned.

4.12 Variation of Temperature with Height

The results from the model did not take account of stratification so minimum temperatures will be lower than the mean values computed during the simulation.

For information about stratification we must look at the real test results. There is a 17ºC temperature difference between the air in the sleeping zone and air a metre above floor level. This dramatic variation in temperature is undesirable. The shelters were deliberately tested as a worst case with no activity inside. In reality, at least during the day, the movement of people inside would mix the layers up. During the night, providing the occupants have enough clothing and bedding, the necessary comfort levels will be realised in still conditions only. There are also practical issues regarding the use of the stove and keeping it stocked so that heat input remains high throughout the night. The effect of 'turning off' the stove led to a rapid temperature drop.

The solutions to the stratification problem are limited. The first is to ensure that the air inside the tent is thoroughly mixed, either by the occupants or artificially by fans.

Another solution to stratification could be to vary the U-values of the shelter. Presently, the shelter is extremely well insulated in its dome but loses heat through the floor. Increasing insulation anywhere in the shelter also increases its weight, volume and cost so perhaps a scheme which thins out the over-insulated roof in exchange for a thicker floor could reduce stratification without increasing weight. As this solution gets more complicated so the manufacturing costs also rise. One of the major design principles has always been to keep fabrication easy and cheap; extra detailing of this sort would need careful costing.

4.2 Condensation Performance

4.21 Formation of Condensation

Although humidity levels were marginally higher in the Web Dynamics tent, condensation only developed in two very localised areas. No ice or water was visible inside the shelter even at the sites of cold bridges like the poles and purlins. Frosting between the wadding and the outer membrane was widespread but as far as the comfort of the occupants is concerned, condensation and moisture or frost build up beyond the wadding is not a problem. The higher humidity was a result of fewer air changes and a lower mean temperature.

It is possible to postulate several long term scenarios. Water vapour condensing over a long period of time and 'water-logging' the wadding would be detrimental to the thermal performance of the shelter because substituting the air in the insulation for trapped water reduces the tog value.

The counter effect might be the growth of an icy film. As the icy layer thickens, its thermal properties may start to become significant in the U-value calculations for the tent[8]: the ice covering the outer sheet itself becomes a barrier to heat transfer out of the shelter. If the improved resistance to heat flow due to the ice is enough to raise the skin temperature and stop further frosting, then, at a critical cut off, the icy layer will stop getting thicker and allow further condensation to run off and drain to the ground. Ideally, this would happen before the layer of ice adds enough to the weight of the material to became structurally significant.

Either way, the most desirable outcome would be for water vapour to pass through the wadding and the outer sheet without condensing or freezing. For further analysis of condensation within the shelter walls, much more detailed data about the vapour permeability of the composite materials must be known. The research team have discussed with Web Dynamics the possibility of future tests to thoroughly investigate other material properties such as permeability.

4.22 Humidity Levels, Comfort and Health

CIBSE recommend a maximum, comfortable relative humidity to be 70%. Recent studies have shown that mould can form even without much condensation after prolonged exposure to such high humidity. Both shelters are too humid for comfort during testing but the evaporation rate chosen during the design of the experiment was a maximum, worst case. Production of water vapour is proportional to the activity of occupants. During times of peak activity, movement in and out of the shelter should disperse moisture content to an extent.

Overcoming high humidity requires some kind of air conditioning. In its most crude sense this simply means allowing drier air from outside to infiltrate into the tent and force out the most damp air. In this case the outside air is extremely cold and its introduction would lead to additional heat losses.

The design compromise is in allowing ventilation and mixing without dramatically increasing the heat losses.

4.3 Improving the Experiment and the Model

Firstly, a test rig with more, uniformly spaced temperature sensors would give better resolution of a mean temperature. Secondly, tests without the presence of water vapour must be carried out as this affects losses via infiltration. Thirdly, the local values for determining dew point temperatures did not correspond to actual condensation. Sensors nearer to the surfaces in question would give more reliable predictions about condensation.

Improvements to the model are mainly to be found in the calibration method which gets better with the improved experimental techniques suggested. More than one node inside the tent could be useful in modelling stratification but the usefulness of pursuing an increasingly complicated and highly accurate model may be outweighed by the uncertainties that exist in the real life use of the shelter. It may be more useful to carry out an architectural or sociological survey of shelter use and occupant response in the field now that we have a ball park figure for fuel requirement.

4.4 Design Issues

4.41 Heat Losses and Ventilation

This experiment has demonstrated that designing for comfort involves controlling infiltration to achieve the best balance between keeping the air fresh and maintaining an adequate and uniform mean temperature.

Obviously, there is more leeway with this question if the tent is only specified for use in conditions down to –5ºC or -10ºC. With a lower outside temperature, heat loss through the materials is lower and a higher air change rate for equivalent internal temperature is possible. Better ventilation will not necessarily aid mixing because it is difficult to control natural air flows through a shelter but it will help to purge the very damp air. The next design stage could be to develop a means of promoting air exchange by using flues, flaps or holes.

4.42 Light Levels

Under the tube lighting of the freezer, visibility inside the Web Dynamics shelter was next to nothing. Even when the shelter was set up outside in sunlight, light levels inside were unsatisfactory. The dark blue outer membrane could be made from a lighter colour but essentially it is the wadding that blocks most light.

Here again a quandary arises: by thinning the wadding to allow light through, the tog value could also drop thus compromising the thermal performance of the structure. The introduction of windows has been suggested. Were these to be placed high up in the doors sections, they might also act as vents to cool the hottest upper layer of air.

The Oxfam tent, with its transparent doors, was light enough to work in even inside the artificially lit freezer.

4.43 Fabrication

It was the sock-like assembly of the Web Dynamics materials which gave it an advantage as far as minimising heat loss through cracks. While this feature ought to be retained as far as thermal performance is concerned, it reduces some useful infiltration. Perhaps by cutting the material into separate panels, fabrication costs could be reduced and natural buoyancy and wind driven ventilation improved.

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Word Count: 10,913

APPENDICES

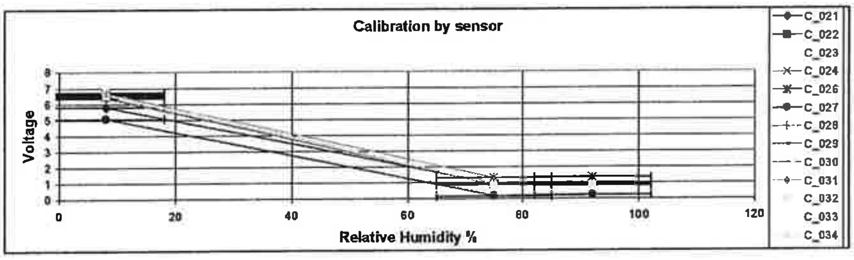
APPENDIX A

Calibration Results for Humidity Sensors

	C 021	C 022	C 023	C 024	C 026	C 027	C 028	C 029	C 030	C 031	C 032	C 033	C 034	C 035
8	5.7835	6.4198	6.5463	6.427	6.6025	5.0598	6.3586	6.68915	6.6552	6.639	6.7309	6.5561	6.6394	6.6623
75	0.9261	0.8606	0.9162	0.9003	0.9041	0.1518	0.8704	0.8901	0.8707	0.9047	0.8916	0.8689	0.9263	1.285
92	0.8727	0.8404	0.8869	0.8656	0.8517	0.2123	0.8416	0.8457	0.8991	0.9846	0.8359	0.8264	0.8714	1.3149

Steady State Results at Different Humidities

92%				75%				8%			
21	0.8727	29	0.8457	21	0.9261	29	0.8901	21	5.7835	29	6.8915
22	0.8404	30	0.8514	22	0.8606	30	0.8707	22	6.4198	30	6.6552
23	0.8869	31	0.9155	23	0.9162	31	0.9047	23	6.5463	31	6.639
24	0.8656	32	0.8359	24	0.9003	32	0.8916	24	6.427	32	6.7309
26	0.8517	33	0.8264	26	0.9041	33	0.8689	26	6.6025	33	6.5561
27	0.2123	34	0.8714	27	0.1518	34	0.9263	27	5.0598	34	6.6394
28	0.8416	35	1.3149	28	0.8704	35	1.285	28	6.3586	35	6.6623



(Sensor21+6.1695)/-0.0624
(Sensor22+6.8548)/-0.0711
(Sensor23+6.9883)/-0.0721
(Sensor24+6.8619)/-0.0708
(Sensor26+7.0536)/-0.0732
(Sensor27+5.431)/-0.0621
(Sensor28+6.7895)/-0.0703
(Sensor29+7.1468)/-0.0744
(Sensor30+7.0997)/-0.0736
(Sensor31+7.0712)/-0.0725
(Sensor32+7.1935)/-0.075
(Sensor33+7.0047)/-0.0729
(Sensor34+7.0921)/-0.0734
(Sensor35+7.075)/-0.06884

APPENDIX B

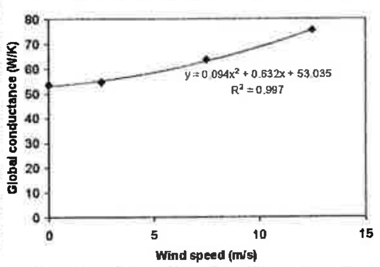
Calculation of U-values and Infiltration Rates

Oxfam

FLOOR					
descrip	Thickne	Conduc	Resista	U-value, W/m2.K	
Rsi			0.15		
LDPE	0.0003	0.04	0.0063		
closed c	0.01	0.035	0.2857		
			0.442	2.2626	
EDGE					
Rsi			0.123		
LDPE	0.0003	0.04	0.0063		
closed c	0.005	0.035	0.1429		
R			0.178		
closed c	0.005	0.035	0.1429		
LDPE	0.0003	0.04	0.0063		
Rso			0.055		
			0.6542	1.5286	
WALL/ROOF					
Rsi			0.123		
LDPE	0.0003	0.04	0.0063		
Expand	0.15	0.044	3.4091		
LDPE	0.0003	0.04	0.0063		
Rso			0.049		
			3.5936	0.2783	
			4.6898	4.0695	
				0.2132	
Mensuration					
Internal dimensions: 3.74			U-value	Conductance, W/K (ambient)	W/K
floor are	13.932	w.d	2.2626	5.5855	conductances mulipied
front/rea	10.898	pi.r^2	1.5286	19.157	by an uncertainty factor
wall/roo	21.884	pi.r.l	0.2783	7.003	of 15 %, due to bridging etc
Total ar	46.713		4.0695	0.2457	
Volume	20.379	(pi.r^2/2	TOTAL	31.991	FABRIC CONDUCTANCE
				21.044	APPROX BUOYANCY-DRIVEN INFILTRATION CONDUCTANCE
Infiltratio	3.0979	ac/h	(+/- 30%)	2418.4	
	HEAT LOSS SPLIT (W/K)				
	Fabric fl	5.5855			
	Fabric w	7.003			
	Fabric e	19.157			
	Infiltratio	18.622			
CALCULATED INCREAS			Total vent rate		
0m/s	0	ac/h	3.0979		
2.5m/s	0.1484	ac/h	3.2463		
7.5m/s	1.4888	ac/h	4.5867		
12.5m/s	3.2375	ac/h	6.3354		
A*U W/K	V m3	n	cp @ 1	Q input	delta T
31.991	20.379	3.0979	1006.5	2658	53.544

wind sp	infiltration rate
0	2.7414
2.5	2.8897
7.5	4.2302
12.5	5.9789

Regression Curve Plotted From Tests at Ford



Web

FLOOR					
descrip	Thickne	Conduc	Resista	U-value, W/m2.K	
Rsi			0.15		
LDPE	0.0003	0.04	0.0063		
closed c	0.01	0.035	0.2857		
			0.442	2.2626	
EDGE					
Rsi			0.123		
Waddin	0.05	0.0595	0.84	1.1905	
Rso			0.055		
			1.0183	0.982	
WALL/ROOF					
Rsi			0.123		
Waddin	0.05	0.0595	0.84	1.1905	
Rso			0.049		
			1.0123	0.9878	
			2.4726	0.4044	
Mensuration					
Internal dimensions: 3.74			U-value	Conductance, W/K (ambient)	W/K
floor are	13.932	w.d	2.2626	5.5855	conductances mulipied
front/rea	10.898	pi.r^2	0.982	12.307	by an uncertainty factor
wall/roo	21.884	pi.r.l	0.9878	24.859	of 15 %, due to bridging etc
Total ar	46.713		4.2324		
Volume	20.379	(pi.r^2/2	TOTAL	42.752	FABRIC CONDUCTANCE
				10.283	APPROX BUOYANCY-DRIVEN
Infiltratio	1.5138	ac/h	(+/- 30%)	0	
	HEAT LOSS SPLIT (W/K)				
	Fabric fl	5.5855			
	Fabric w	24.859			
	Fabric e	12.307			
	Infiltratio	18.622			
CALCULATED INCREAS			Total vent rate		
0m/s	0	ac/h	1.5138		
2.5m/s	0	ac/h	1.5138		
7.5m/s	0	ac/h	1.5138		
12.5m/s	0	ac/h	1.5138		
A*U W/K	V m3	n	cp @ 1	Q input	delta T
42.752	20.379	1.5138	1006.5	2658	51.735

wind sp	infiltratio
0	2.7414
2.5	2.8897
7.5	4.2302
12.5	5.9789

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APPENDIX C

Dew Point Tables

WEB DYNAMICS

Table 7.1 Front

Surface	Relative Humidity (%)	Air Temperature (°C)	Dew Point (°C) T_d	Skin Temperature (°C) T_s	T_d - T_s
Floor	80.6	-0.24	-2.7	-0.02	-2.68
Wall	64.4	16.32	9.9	17.67	-7.77
Sides	64.4	16.32	9.9	12.77	-2.87
Roof	83.8	16.09	13.3	14.23	-0.93

Table 7.2 Back

Surface	Relative Humidity (%)	Air Temperature (°C)	Dew Point (°C) T_d	Skin Temperature (°C) T_s	T_d – T_s
Floor	78.4	4.02	0.4	-0.02	0.42
Wall	70.6	21.09	14.5	N/A	N/A
Sides	70.6	21.09	14.5	20.39	-5.89
Roof	86.1	18.28	16.5	19.18	-2.68

OXFAM

Table 7.1 Front

Surface	Relative Humidity (%)	Air Temperature (°C)	Dew Point (°C) T_d	Skin Temperature (°C) T_s	T_d – T_s
Floor	79.6	1.83	-0.9	5.51	-6.41
Wall	65.4	20.57	13.6	19.52	-5.92
Sides	65.4	20.57	13.6	19.29	-5.69
Roof	81.64	21.39	18	26.84	-8.84

Table 7.2 Back

Surface	Relative Humidity (%)	Air Temperature (°C)	Dew Point (°C) T_d	Skin Temperature (°C) T_s	T_d – T_s
Floor	76.35	2.44	-1.1	5.51	-6.61
Wall	63.03	19.13	11.7	N/A	N/A
Sides	63.03	19.13	11.7	17.54	-5.84
Roof	85.44	20.43	17.8	30.02	-12.22

APPENDIX D

Heat Input Required in terms of fuels

Oxfam	988	7204	6619
MJ	3556.8	25934.4	23828.4
	5472	39899.08	36659.08
kg Charcoa	188.6897	1375.83	1264.106
Tonnes	0.18869	1.37583	1.264106
m3 Charco	**1.037793**	**7.567066**	**6.952584**
kg Wood	390.8571	2849.934	2618.505
Tonnes	0.390857	2.849934	2.618505
m3 Wood	**1.016229**	**7.409829**	**6.808114**
Kerosene	171	1246.846	1145.596
	0.206024	1.502224	1.380236
litres	**206.0241**	**1502.224**	**1380.236**

	Islamabad	Kew	Pristina
Web	902	7194	6617
MJ	3247.2	25898.4	23821.2
	4995.692	39843.69	36648
kg Charcoa	172.2653	1373.92	1263.724
Tonnes	0.172265	1.37392	1.263724
m3 Charco	**0.947459**	**7.556562**	**6.950483**
kg Wood	356.8352	2845.978	2617.714
Tonnes	0.356835	2.845978	2.617714
m3	**0.927771**	**7.399543**	**6.806057**
kg Keroser	156.1154	1245.115	1145.25
m3 Wood	0.188091	1.500139	1.379819
litres	**188.0908**	**1500.139**	**1379.819**

Charcoal	29MJ/kg	5.5m3/tonne
Wood	14MJ/kg	2.6m3/tonne
Kerosene	32MJ/kg	830kg/m3

3.6MJ=1kWhr
Assumed efficiency: 65%

APPENDIX E

MatLab Output

WEB

	13	14	15	16	17	18	19	20	21	22	23	24
Air	8.8164	8.6211	8.9716	8.5801	9.1669	8.9106	9.2828	8.6722	9.2175	8.8187	9.3607	9.1182
Floor	-0.02	-0.09	-0.05	-0.03	-0.07	-0.06	-0.027	-0.14	-0.09	-0.19	0.01	-0.33
Roof	17.26	16.7	16.655	16.73	16.375	16.975	16.265	16.93	16.47	16.31	16.875	16.125
Wall	16.565	16.003	16.073	16.06	15.96	16.215	16.258	16.243	16.308	16.165	16.42	16.005
Front D	16.77	17.36	17.26	16.22	17.47	15.69	17.85	16.09	17.28	17.87	16.24	17.76

	25	26	27	28	29	30	31	32	33	34	35	36
Air	9.0444	9.2374	8.5687	9.097	9.0471	9.3568	9.1619	8.8155	9.193	9.2707	9.2746	9.8963
Floor	-0.09	-0.29	-0.14	-0.12	-0.26	0.03	-0.38	-0.39	-0.64	-0.7	-0.34	-0.02
Roof	16.98	16.055	16.72	16.005	16.19	16.645	15.815	16.575	16.12	15.965	16.79	17.12
Wall	16.28	16.043	16.068	16.115	16.205	16.398	16.083	16.248	16.228	16.393	16.863	17.128
Front D	15.69	17.56	16.41	17.59	17.64	16.54	18.07	16.78	17.42	18.83	18.3	18.34

OXFAM

	30	31	32	33	34
Air	10.16	10.727	11.46	12.03	10.27
Floor	5.1	5.57	6.56	4.81	5.51
Roof	27.23	28.65	29.98	27.86	28.43
Wall	17.69	18.53	19.45	17.99	18.41
Front D	18.5	20.63	21.17	17.77	19.518

TEST

Average	WEB	OXFAM
Air	9.4567	10.929
Floor	0.0381	5.51
Roof	16.773	28.43
Wall	16.68	18.414
Front D	17.743	19.518

Once 'V' the final volume data matrix has been set up, MatLab creates a 'movie' using the following code.

```
%Setting Up Final Grid For Interpolated Slice
xfinal=0:.15:3.6;
yfinal=0:.15:3.6;
zfinal=0:.075:1.8;
[xfinal,yfinal,zfinal] = meshgrid(xfinal, yfinal, zfinal);
V=zeros(size(xfinal));
V=interp3(layerx, layery, layerz, layers, xfinal, yfinal, zfinal);
V(((xfinal-1.89).*(xfinal-1.89)+zfinal.*zfinal)>3.6)=NaN;
     slice(xfinal,yfinal,zfinal,V,[],[0.45 3.15],[])
     set(gca,'CameraPosition',[-24 -11 10])
     caxis([-20 44]);
     M(k)=getframe;
end

MakeQTMovie('start','fordtest1.mov');
MakeQTMovie('quality',1);
movie(M(80));
MakeQTMovie('framerate',5);
MakeQTMovie('addfigure');
MakeQTMovie('finish');
```

The MakeQTMovie function was downloaded from: http://www.interval.com/papers/1999-066/.

The linear interpolation for the temperature-by-area calculation is as follows.

```
element_area=0.15*0.075;
aslice1=vnew1*element_area;
first_sum1=sum(aslice1);
second_sum1=sum(first_sum1);
C1=second_sum1;
Q1=C1-(2*200*element_area);
D1=find(vnew1~=200);
E1=size(D1);
temp_first_slice=Q1/(E1(1,1)*element_area)
```

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