UNIVERSITÉ DE ROUEN

University of Brighton

Centre for Sustainability of the Built Environment

Case Study Report

THE BRIGHTON EARTHSHIP: EVALUATING THE THERMAL PERFORMANCE

PROJECT PART-FINANCED BY THE EUROPEAN UNION

European Regional Development Fund

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Front Cover Images:

Top: Brighton Earthship Winter 2005, after the installation of photovoltaics, solar hot water heating and wind turbine. (Hewitt, 2005)

Bottom: Brighton Earthship Winter 2004-5 (Durabuild, 2004)

Executive summary

The Brighton Earthship, an off grid building which is intended to be self sufficient and based on the designs of Mike Reynolds in Taos, New Mexico is in the final stages of construction in Stanmer Park, East Sussex. Durabuild has been monitoring the development of the project and taking numerous readings from the buildings internal environment and structure in an attempt to understand the thermal performance of this type of structure, the first of its type in England. This report focuses on explaining the principles behind the building, the monitoring regime undertaken and analyses the data which have been collected so far.

The principal of thermal mass has been used in traditional buildings to retain heat and to reduce temperature swings inside the building, acting as a battery for heat, being charged when heat is available from solar gain through glass and providing heat to the internal space when its conditions fall below that of the store.

Early results of both internal and external conditions show internal conditions to be consistently warmer than outside, responding to incident solar radiation. The building at the time of these results however was still under construction and unoccupied and therefore not truly reflective of comfort conditions in the completed building. The variation in temperatures recorded indicates that the thermal battery effect is unikely to have reached stable cyclic conditions. However, ongoing measurements will be used to evaluate its thermal performance and future work will also expand to look at other aspects of the building.

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Acronyms & abbreviations

CIBSE: Chartered Institution of Building Services Engineers

ESRW: Earth Sheltered Rear Wall

AT: Air Temperature

IESVE: IES Virtual Environment

LCN: Low Carbon Network

A/ Introduction & Project Description

With accelerating implementation of global and national policies and agendas on reducing the uncertain effects of predicted climate change there has been an increasing recognition that the built environment contributes to this challenge. Approximately 50% of all greenhouse gas emissions (UK figures) are related to the construction, operation and occupation of buildings, both commercial and domestic (Harman & Benjamin, 2004) and with 26% of the end use of all electricity generation as space heating for these buildings (DTI, 2003) their thermal performance is one of the most significant areas in this field for investigation.

The use of earth to shelter buildings is not a new solution. Indeed it has been used for centuries for a number of reasons, for example; defence, camouflage and protection against fires and in response to high population densities (Silber, 1991). Over the last 25-30 years the benefits of earth-sheltering to influence thermal performance thereby reducing space heating demands and CO_2 emissions (Littlewood & Geens, 2001) in response to economic and environmental energy consumption has become one of the main factors for the development of this type of construction.

One particular type of building which has heavily incorporated earth-sheltering into its ethos is a design known as an 'Earthship', which has been developed and pioneered by US architect / ‘biotect’ Michael Reynolds. Reynolds has been refining these designs since the early 1970’s, largely in Taos, New Mexico, where many buildings of varying design and specification have been completed. Earthships are so named as the concept centres on them being *‘independent vessels’* (Reynolds, 1990) which operate on a self sufficient basis and are constructed largely from recycled and reclaimed materials. The ethos of Earthships includes; utilisation of low embodied energy materials, passive solar heating and cooling, photovoltaic power systems, rainwater harvesting, solar hot water heating along with black and grey water treatment systems (Earthship Biotecture, 2005).

Earthships are modular in design and, although there is a significant degree of variation which can be achieved using the main design principle of glass and mass (angled glass to trap the solar gain at particular times of year and mass to act as a heat source and heat sink accordingly). A fuller explanation of the 'glass and mass principle is given in section F. An Earthship will often consist of three main modules.

- Sunspace or Conservatory: (a botanical water treatment cell can be seen within the sunspace in Figure 1 below). This is not always separated from the nest in climates such as Taos, but is used as a buffer space for the European climate (Howarth, 2004)

Figure 1(left): Earthship with combined nest and sunspace module in Taos, New Mexico (Earthship Biotecture cited in Howarth, 2004).
Figure 2 (right). Buffer sunspace / conservatory (under construction) (Durabuild 2004) (right).

- Nest Module: the principal unit of design which is earth sheltered using walls constructed of old vehicle tyres rammed with local earth to provide thermal mass and utilise a waste product which is in plentiful enough supply that in some respects could be referred to as a modern natural resource.

Figure 3: Nest modules under construction in Taos, New Mexico (Earthship Biotecture cited in Howarth, 2004).

Figure 4: Construction of the nest module thermally massive rear wall, Brighton Earthship (Hodge, undated).

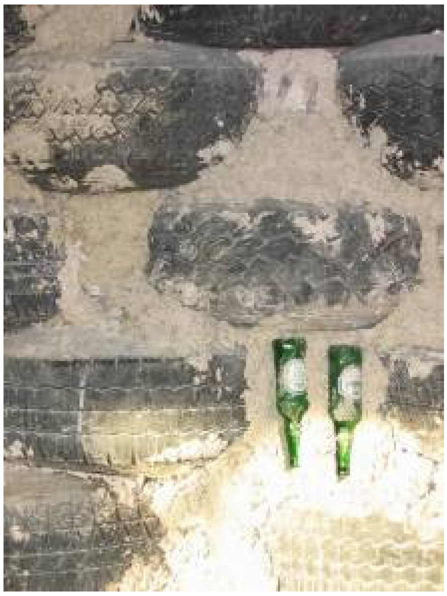


Figure 5 (left): Unit of construction, a tyre rammed with local chalk from the Brighton Earthship (Howarth, D 2004).
Figure 5 (right): Tthe structural wall of rammed earth tyres held in eco-crete cement (Durabuild, 2004).

- The Hut

Hut modules are a variation in the earth sheltering design to provide a round interior space, using the same tyre-wall construction as the nest although sheltered partially around the circumference and not on three sides like the nest module.

Figure 6: Construction of the hut module, Brighton Earthship, 2004 (Howarth, 2004) (The completed hut is shown on the picture on the front cover).


Figure 7: Images of completed Earthships in Taos, New Mexico showing variation in design (Larsen, undated).

B/ Project history and details: The Brighton Earthship.

Earthships have, until relatively recently been constructed exclusively in Taos, New Mexico, with the exception of some demonstration projects in other countries. The Brighton Low Carbon Network, responsible for the construction of the Brighton Earthship, was formed after a talk given by Mike Reynolds, in April 2000 in Brighton. Funding and planning permission allowed work to begin in Stanmer Park, on land owned by Brighton and Hove City Council in July 2002. Initial training for the construction was provided by the American construction team.

The external envelope of the shell is complete (shown in Figure 8 below) and the next stage of internal finishes and installation of the renewable services is ongoing. The International 'Earthship' Summit, hosted at the University of Brighton allowed the American team another opportunity to visit the project and advise on completion.

The Brighton 'Earthship' is a three module system, with a conservatory / sun space separated as a buffer zone from the main nest module, and with a hut module to the left of the plan.

Figure 8: The Brighton Earthship winter 2003 (Low Carbon Network cited in Lam, M, 2005).

The Brighton Earthship, built in the very northern part of Stammer Park, near Stanmer Village (East Sussex, UK) is entirely off grid with no mains water, or electricity.

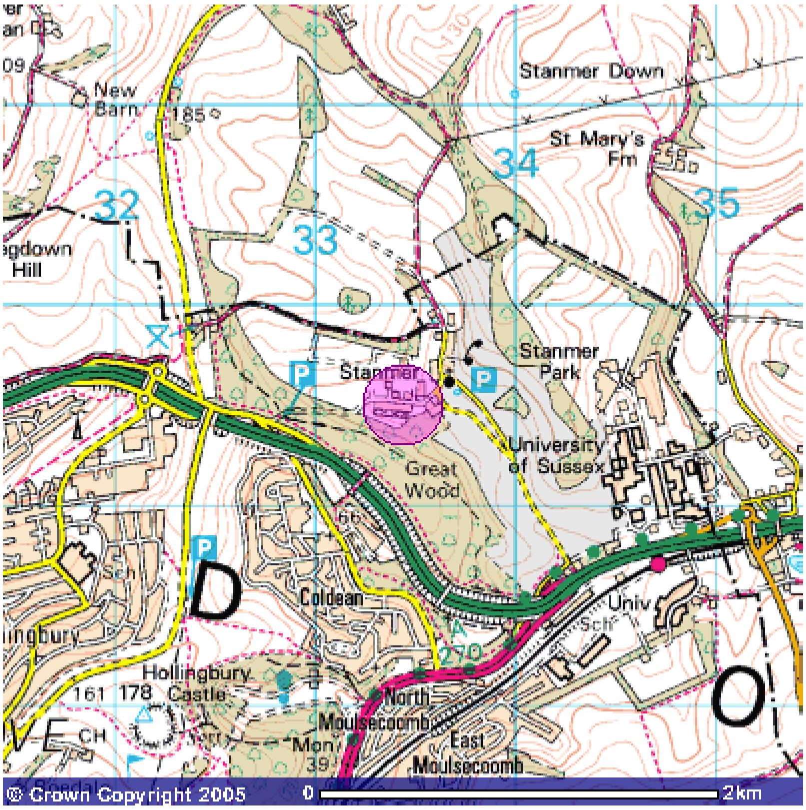


Figure 9: Location of Stanmer Park and Village, East Sussex, UK (Village marked by dot). (Image produced from the Ordnance Survey Get-a-map service. Image reproduced with kind permission of Ordnance Survey and Ordnance Survey of Northern Ireland).

C/ Technical details of the building/ case study

- Completion of the building: Due 2006
- Cost: 180K approx.
- Ventilation systems: natural.
- Hot water supply: solar flat plate hot water heating system.
- Heating and Cooling: heat storage through earth sheltering and heat sink cooling along with natural ventilation. Heating also provided by a 15kW wood pellet boiler.
- Generation of electricity: generates electricity through photovoltaics and 900w whisper H40 wind turbine.
- Project developer: Low Carbon Network, Brighton.
- Architect: RH Partnerships (Brighton) based on drawings by Michael Reynolds (United States).
- Contractor: volunteer labour.
- Service engineers: John Packer Associates.
- Gross Floor area: 133.62 m^2 or 1438.274 square feet.

- [nest 14m by 6m (84m^2), conservatory 2.5m by 12m (30 m^2), hut 5m diameter (19.62m^2)]

Details of sustainable feature(s) of case study building

Energy

- Photovoltaic cells.
- Solar hot water heating
- Passive solar.
- Insulation – standard Rock wool (donated).
- Wind turbine.
- Buffer Zone: Conservatory Module.
- Thermal Mass: composite of car tyres rammed with local chalk and infilled with glass bottles and aluminium cans.
- Earth Sheltering: Earth sheltering on north and West, and East faces.

Materials

- Local materials: many materials donated / or collected locally.
- Recycled materials: tyres, aluminium cans, glass bottles, many wooden internal fittings, stone for nest floor (off cuts from stone masons).

Health

- Building Management Systems: WOM (Water Organising Module) & POM (Power Organising Module).

- Natural ventilation: 2 opening skylights in nest module and plenum skylight on roof of hut module.
- Water source & treatment: rainwater collection and greywater / blackwater botanical treatment cells.

E/ Aim and Objective of study

The opportunity for monitoring the Brighton Earthship by the Durabuild project was presented in April 2004 by the Low Carbon Network, when the majority of the structure was complete. Equipment to measure the activity of the thermal mass and the internal environment was specified and purchased during the summer of 2004 and installation completed by November of the same year.

Previous monitoring of Earthship thermal behaviour through monitoring of this type in other Earthships has not been extensive. A study by Grindley & Hutchinson (1996) actively monitoring the internal surface, air and mean radiant temperature, along with external air temperature and insolation in order to calibrate a computer simulation in Tas® appears to be the only published results. However, these data were gathered on a limited number of days and did not look at the internal behaviour of the ESRW thermal mass.

Initial results from monitoring the Brighton Earthship have been analysed in previous publications by Durabuild team members (Ip et al 2005). However, this more detailed Case Study benefits from a longer period of data collection and more detailed analysis of the various parameters being measured. This Case Study forms the first major report in what will be long term monitoring of the building during its completion and subsequent occupation. Anecdotal evidence points to the conclusion of the thermal battery effect (described in more detail in the next section) of the tyre wall takes two years to reach stability and maximum effectiveness. One of the central objectives of the research begun under the Durabuild project and to be continued by the Centre for Sustainability of the Built Environment is to gather over a long enough period to assess this.

F/ Summary of sustainable feature: Earth sheltering & thermal performance

The phrase ‘glass and mass’ is widely used by proponents of ‘Earthships’ to describe the main design principle influencing thermal performance characteristics. Figure 10 depicts this principle showing the maximisation of the winter sun angles and minimisation in the summer through the glazed solar façade.

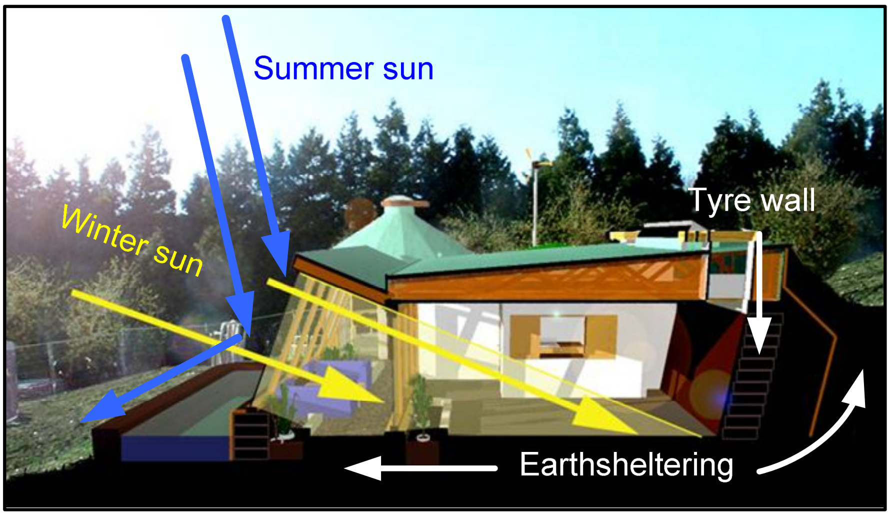


Figure 10: Schematic of solar gain to Earthship (unannotated picture Larsen, undated, cited in Howarth, D, 2004, annotations Durabuild, 2005).

Thermally massive, earth-sheltered, rear walls (ESRW) are constructed of vertically stacked layers of reclaimed vehicle tyres. These are rammed with earth and precede a layer of pure compacted earth (up to a depth of 1.5 metres) before a plastic barrier and finally the undisturbed earth behind. In practice gaps left because of the circular shape of the tyres have been in filled with other end of useful life materials such as aluminium cans or bottles.

In the UK earth temperatures below the surface become constant at the frost line to between 11 and 13°C (Action Renewables, 2005). However, nearer the surface temperatures are less stable, being influenced by solar radiation and local factors influencing heat exchanges. The important factor, whichever thermal soil zone forms part of the earth sheltering of a building is that the temperatures are more stable than diurnal cycles thus allowing it to act as a heat source to warm the internal environment in winter and a heat sink to provide cooling in summer (Givoni & Katz 1985, Reynolds, 1990, 2000).

The design of an Earthship utilises the tyre wall to act as a thermal battery (Reynolds 1990, Reardon et al, 2005). A relationship between the south facing solar gains and the thermal storage properties of the rear wall structure is exploited. The desired effect of regulating of internal temperature fluctuations in relation to the influence of external temperature cycling which is allowed by thermally massive structures, (Goodhew & Griffiths, 2005) is one aspect of Earthship thermal performance examined within this paper.

G/ Methodology

A range of 30 different sensors were installed in the Brighton Earthship during autumn of 2004. The following two diagrams show the plan of the Brighton Earthship and sensor location.

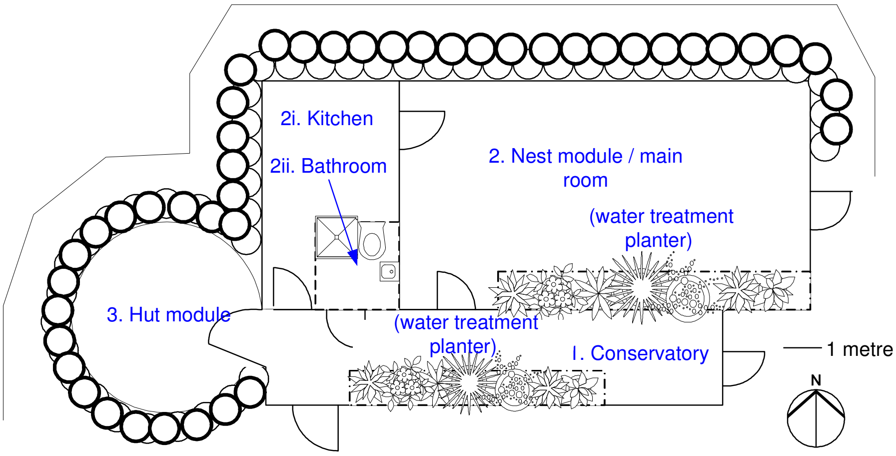


Figure 11: Brighton Earthship plan (Ip et a,l 2005).

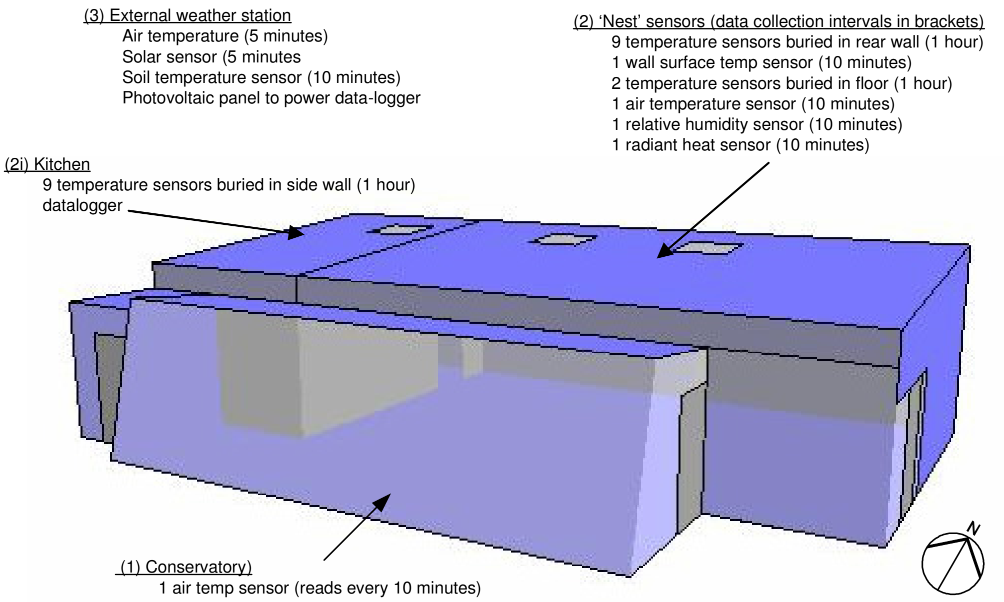


Figure 12: IESVE model of Earthship showing sensor location and details of data collection intervals. (NB: there are also relative humidity, standard air temperature sensors, and an air temperature sensor within a trombe wall in the hut, not shown in the IESVE model.)

The positioning of the temperature sensors to measure the ESRW thermal mass in the two main walls at the rear of the nest and the side of the kitchen is within holes drilled at intervals of three, at different depths into the wall, and at three different heights vertically. It was decided to make these intrusions uniform in order to gain data from an evenly spaced 'grid', aiding analysis.

This grid is represented in the diagram below.

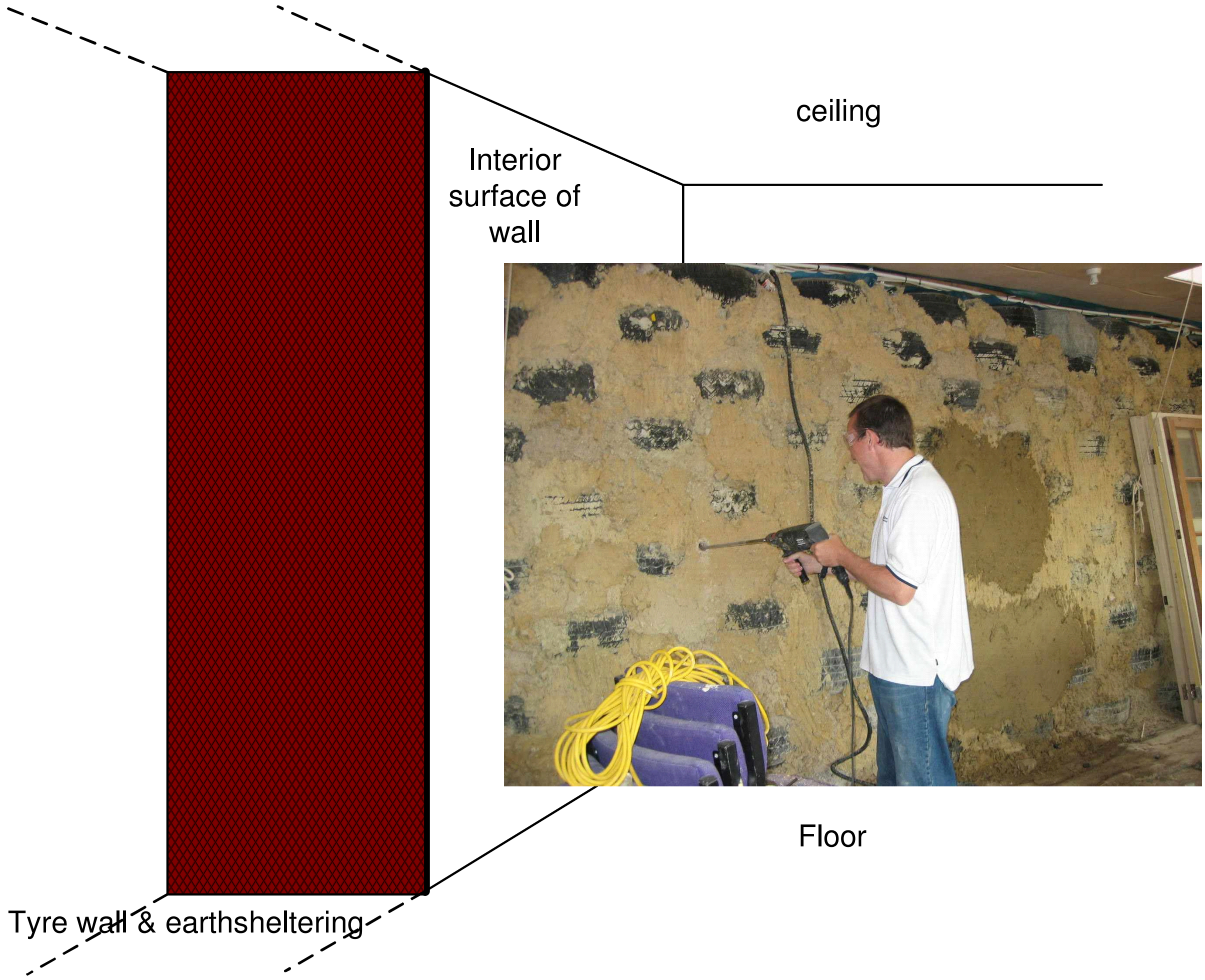


Figure 13: Sensor Location in ESRW (sensor position is to scale)
(NB. In reality the surface of the wall since sensor installation has been covered with at least two more layers of plaster, making their depth into the ESRW potentially 10cm deeper than originally recorded).

Drilling the holes for the sensors, however, represented three main challenges; causing minimal disturbance to the already structurally complete wall, the requirements of the sensors, and the drilling itself. Considering the potential final aesthetic, and to gain readings as accurately as possible with the sensors being in contact with as much material in the wall as possible (as opposed to measuring the air temperature of a hole in the wall). It was aimed to have a hole with a relatively small diameter (less than 25 mm). Using a custom made metre long drill bit it was still necessary to use a hole cutter to initially break through the first edge of the tyre. The composite nature of the walls including the rubber of the tyres and the steel braiding within them was somewhat of an unexpected element and the heat generated by the drill bit made the access through either side of the tyre possible, yet when the drill was removed, the natural cooling of the rubber caused the hole in the tyres to close over. Furthermore, it became apparent that encountering glass bottles and cans within the walls meant it

was impossible to continue with some of the attempted entry points and the exact planned position of the sensors had to be accommodated around where hole drilling was ultimately successful.

Consequently, the planned uniformity of differing depths was not achieved accurately to the centimetre. This small difference is not thought to affect the efficacy of the dataset under collection.

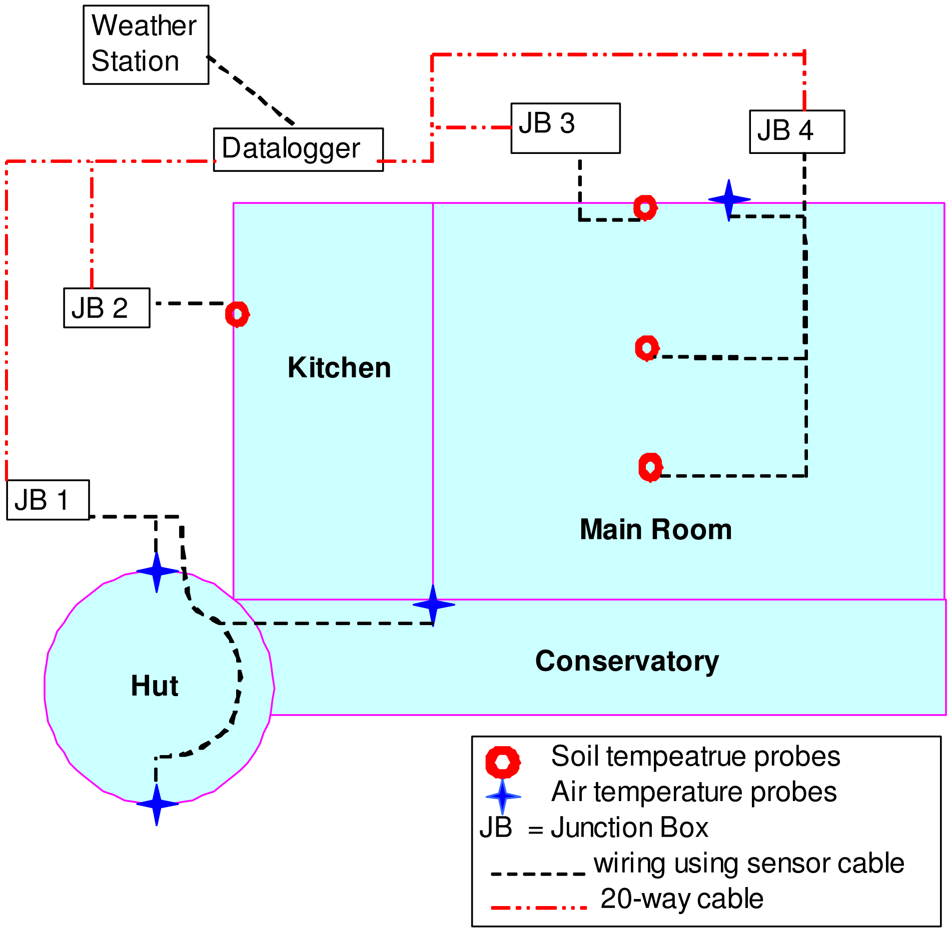
H/ Equipment and Experimental Set up.

All sensors connected to the main datalogger were supplied by Delta T Devices Ltd. Both soil and air temperature sensors are 2k thermistors. The soil sensors are contained in a stainless steel sheath allowing for burial with a range of -20+80℃ and an error of +/- 0.2 ℃ and a response time of 6 seconds (Delta T, 2002). Air Temperature sensors are +/-0.1℃ accurate over -20℃ to + 60℃, also with a six second response time (Delta T, 2002). The radiation sensor measures incident solar radiation. Incident solar radiaton can be defined as the solar energy incident on a given area over a specific period of time and is usually given in kilowatt-hours per square metre.

The main datalogger is also supplied by Delta T and is a 45 channel analogue logger which at present uses 30 channels to record data. Power is provided by a photovoltaic panel attached to the external sensor mast, with back up batteries to supply power when sufficient solar power is not available.

There are also two small independent dataloggers from a different manufacturer which record temperature and humidity within the nest and the hut to allow two Delta T sensors to record surface temperatures of the wall and not air temperature as was their original function.

The following diagrams help clarify the monitoring equipment set up.



			Location		
Channel/ No.	**Sensor Type**	**Sensor code**		Sensor vertical level	Sensor depth (excluding probe)
1					
2 (JB1)	AT2- air temp	79	Between hut wall and glass		
3 (JB1)	AT2- air temp	80	On wall of conservatory		
4 (JB2)	ST1-soil temp	1966	Kitchen	Top	32 inch (0.81m)
5 (JB2)	ST1-soil temp	1988	Kitchen	Top	20 inch (0.51m)
6 (JB2)	ST1-soil temp	1968	Kitchen	Top	10 inch (0.25m)
7 (JB2)	ST1-soil temp	1967	Kitchen	Middle	30 inch (0.76m)
8 (JB2)	ST1-soil temp	1969	Kitchen	Middle	20 inch (0.51m)
9 (JB2)	ST1-soil temp	1970	Kitchen	Middle	10 inch (0.25m)
10 (JB2)	ST1-soil temp	1971	Kitchen	Low	32 inch (0.81m)
11 (JB2)	ST1-soil temp	1986	Kitchen	Low	20 inch (0.51m)
12 (JB2)	ST1-soil temp	1987	Kitchen	Low	10 inch (0.25m)
13 (JB3)	ST1-soil temp	1965	Main room	Top	27 inch (0.69m)
14 (JB3)	ST1-soil temp	1973	Main room	Top	20 inch (0.51m)
15 (JB3)	ST1-soil temp	1972	Main room	Top	10 inch (0.25m)
16 (JB3)	ST1-soil temp	1974	Main room	Middle	30 inch (0.76m)
17 (JB3)	ST1-soil temp	1977	Main room	Middle	20 inch (0.51m)
18 (JB3)	ST1-soil temp	1976	Main room	Middle	2 inch (0.05m)
19 (JB3)	ST1-soil temp	1964	Main room	Low	30 inch (0.76m)
20 (JB3)	ST1-soil temp	1963	Main room	Low	20 inch (0.51m)
21 (JB3)	ST1-soil temp	1975	Main room	Low	2 inch (0.05m)
22 (JB4)	AT2- wall temp	81	Main room wall temp		
23 (JB4)	ST1-soil temp	1989	In the ground of main room	(1m away from the wall)	
24 (JB4)	ST1-soil temp	1990	In the ground of main room	(1m away from the planter)	
25	LINK	LINK	LINK	LINK	LINK
26 (JB5)	ST1-soil temp	2025	Weather station, in the ground(cable length 25m)		
27 (JB5)	AT2- air temp	77	Weather station		
28 (JB5)	GS1-solar	F-238	Weather station		
29 (JB1)	AT2- wall temp	78	On the wall of Hut		
30	Radiant temp	AG-U	Main room wall		

Figure 14: Basic wiring plan of Earthship sensors and sensor reference chart.

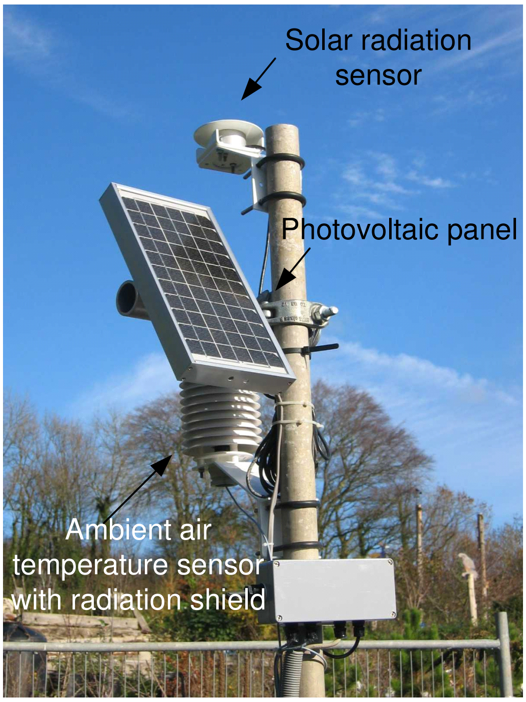


Figure 15 (left): The external weather station sensors (Durabuild, 2004).
Figure 16 (right): the datalogger housed in the kitchen (Durabuild, 2004).

I/ Measurements

Data from the main datalogger and the two miniature independent loggers is downloaded approximately every three-four weeks before the loggers memory is full, and the logging cycle begins again. Data is then imported into Excel for manipulation and analysis.

J /Results

Downloaded data from the DL2e datalogger and the Dickson Temperature and humidity loggers has been collated into Excel Spreadsheets and the data divided into seasons based on the vernal (spring) and autumnal equinoxes, along with the winter and summer solstices as well as calendar months. This allows discussion and analysis along seasonal heating and cooling seasons, and also by month. There is no standard demarcation within the field of absolute heating and cooling seasons so analysis largely focuses on winter as the main cooling season and summer as the main heating season with data blocks available for autumn and spring so that a transition phases can be assessed if needed.

With such a large amount of data (30 channels taking readings at intervals varying from 5 to 10 minutes every day since November 2004) to provide the full dataset would be essentially meaningless. Therefore before looking into specific elements and patterns in more detail, the data has been collated and descriptive statistics performed over the entire dataset to allow quick examination by both reader and author. The following two tables provide this data by both month and season.

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Table 1: Seasonal summary of data from Earthship and descriptive statistics (all channels).

Sensor area	Sensor type / Information	Exact Location	Sensor Reference	Season	Average (°C unless stated)	Maximum (°C unless stated)	Minimum (°C unless stated)	Range (°C unless stated)	Comment
Sensor area	Sensor Information			Summary statistics by Season					green = complete season recorded
Internal temperature and humidity	Radiant Temperature (black globe)	nest	AG-U (30)	Autumn 2004 22 Sep 16.30 to 21 December 12.41					*no sensor, installation Feb 21st 2005*
				Winter 2004-5 21 December 12.41 to Mar 20th 12.33	13.14	21.9	11.09	10.1	incomplete season (Feb 21st to Mar 20th)
				Spring 2005: March 20th 12.33 to June 21st 06.46 ar	17.03	22.94	13.65	9.29	incomplete season (20 Mar - 20 May)
				Summer 2005: June 21 06.46 am to Sept 22 22.23 pm					*data collection ongoing*
	Surface temperature	hut	AT2-78	Autumn 2004					*no sensor, installation 03 Feb 2005*
				Winter 2004-5	12.82	19.03	11.19	7.84	incomplete season (04 Feb - 20 Mar)
				Spring 2005	17.85	23.24	14.77	8.47	incomplete season (20 Mar - 20 May)
				Summer 2005					*data collection ongoing*
	Suface temperature	nest	AT2-81	Autumn 2004					*no sensor, installation 03 Feb 2005*
				Winter 2004-5	13.14	17.24	11.91	5.33	incomplete season (04 Feb - 20 Mar)
				Spring 2005	16.95	23.48	14.24	9.24	incomplete season (20 Mar - 20 May)
				Summer 2005					*data collection ongoing*
	Air Temperature	hut	AT2-78	Autumn 2004	12.73	18.02	10.78	7.24	incomplete season (readings from 11.36am 25/11/04 due to sensor being connected to previous faulty chann
			AT2-78 / Dickson 04366241	Winter 2004-5	15.79	24.56	9.89	14.67	incomplete month, missing data from 03 Feb to 21st Feb when sensors swapped to different uses
			Dickson 04366241	Spring 2005	16.13	29.6	13.6	16	complete season
			Dickson 04366241	Summer 2005					*data collection ongoing*
	Air Temperature	nest	AT2-81	Autumn 2004	13.64	35.92	10.64	25.23	incomplete season (04 Nov - 21 Dec). Hig readings at start due to gas blowers used to dry out plaster
			AT2-81 /Dickson 04366224	Winter 2004-5	13.1	21.39	10.85	10.54	incomplete month, missing data from 03 Feb to 21st Feb when sensors swapped to different uses
			Dickson 04366224	Spring 2005	15.4	27.5	13.7	13.8	complete season
			Dickson 04366224	Summer 2005					*data collection ongoing*
	Air Temperature	conservatory	AT2-80	Autumn 2004	13.74	25.26	9.03	16.23	incomplete season (04 Nov - 21 Dec)
				Winter 2004-5	13.49	28.04	8.78	19.26	complete season
				Spring 2005	20.59	29.88	14.48	15.4	incomplete season (20 Mar - 20 May)
				Summer 2005					*data collection ongoing*
	Air Temperature	in between trombe wall conservatory	AT2-79	Autumn 2004	14.3	28.96	10.56	18.4	incomplete season (04 Nov - 21 Dec)
				Winter 2004-5	13.71	30.98	9.37	21.61	complete season
				Spring 2005	18.8	31.33	12.48	18.85	incomplete season (20 Mar - 20 May)
				Summer 2005					*data collection ongoing*
	Relative humidity	Nest	Dickson 04366224	Autumn 2004					*no sensor, installation Feb 21st 2005*
				Winter 2004-5 % RH	60.25	67.5	51.2	16.3	incomplete season (Feb 21st to Mar 20th)
				Spring 2005	67.46	82.4	38.5	43.9	complete season
				Summer 2005					*data collection ongoing*
	Relative humidity	Hut	Dickson 04366241	Autumn 2004					*no sensor, installation Feb 21st 2005*
				Winter 2004-5 % RH	59.07	67.3	51.5	15.8	incomplete season (Feb 21st to Mar 20th)
				Spring 2005	63.85	76.7	42.3	34.4	complete season
				Summer 2005					*data collection ongoing*
Temperatures of Earth Sheltered Mass	**Nest Floor**	Nest (1 metre from back wall)	ST11989	Autumn 2004	14.71	17.33	21.93	4.4	incomplete season (04 Nov - 21 Dec)
		approx 40 cm deep		Winter 2004-5	13.17	14.32	12.5	1.82	complete season
				Spring 2005	15.65	17.17	14.2	2.97	incomplete season (20 Mar - 20 May)
				Summer 2005					*data collection ongoing*
	Nest Floor	Nest (1 metre from nest planter)	ST1990	Autumn 2004	14.78	17.52	12.71	4.81	incomplete season (04 Nov - 21 Dec)
		approx 40cm deep		Winter 2004-5	13	14.34	12.36	1.98	complete season
				Spring 2005	15.69	17.21	14.6	3.05	incomplete season (20 Mar - 20 May)
				Summer 2005					*data collection ongoing*
	Kitchen Walls	9 sensors buried in a grid at depths / heights	ST1-1966, ST1-1988, ST1-1	**Autumn 2004 (averages)**	0.79m	0.51m	0.25m		incomplete season (04 Nov - 21 Dec)
		A/ depth, 0.79m,0. 51m & 0.25m	ST1-1967, ST1-1969. ST1-1	top profile (1.89m)	15.77	15.43	15.24		
		B/ height, 0.63m, 1.26m & 1.89m from floor	ST1-1971, ST1-1986, ST1-1	middle profile (1.26m)	16.23	15.99	15.58		
				low profile (0.63m)	16.11	15.76	15.26		
	Kitchen Walls	9 sensors buried in a grid at depths / heights	ST1-1966, ST1-1988, ST1-1	**Winter 2004-5 (averages)**	0.79m	0.51m	0.25m		complete season
		A/ depth, 0.79m,0. 51m & 0.25m	ST1-1967, ST1-1969. ST1-1	top profile (1.89m)	12.03	12.15	12.47		
		B/ height, 0.63m, 1.26m & 1.89m from floor	ST1-1971, ST1-1986, ST1-1	middle profile (1.26m)	13.01	13.19	13.15		
				low profile (0.63m)	13.40	13.48	13.32		
	Kitchen Walls	9 sensors buried in a grid at depths / heights	ST1-1966, ST1-1988, ST1-1	**Spring 2005 (averages)**	0.79m	0.51m	0.25m		incomplete season (20 Mar - 20 May)
		A/ depth, 0.79m,0. 51m & 0.25m	ST1-1967, ST1-1969. ST1-1	top profile (1.89m)	15.15	15.54	16.23		
		B/ height, 0.63m, 1.26m & 1.89m from floor	ST1-1971, ST1-1986, ST1-1	middle profile (1.26m)	15.06	15.78	16.18		
				low profile (0.63m)	14.82	15.29	15.53		
	Nest Walls	9 sensors buried in a grid at depths / heights	ST1-1965, ST1-1973, ST1-1	**Autumn 2004 (averages)**	0.73m	0.51m	0.11m		incomplete season (04 Nov - 21 Dec)
		A/ depth 0.73m, 0.51m & 11cm	ST1-1974, ST1-1977, ST1-1	top profile (1.89m)	16.31	15.92	15.50		
		B/ height, 0.63m, 1.26m & 1.89m from floor	ST1-1964, ST1-1963, ST1-1	middle profile (1.26m)	16.47	16.06	15.04		
				low profile (0.63m)	16.34	16.21	14.92		
	Nest Walls	9 sensors buried in a grid at depths / heights	ST1-1965, ST1-1973, ST1-1	**Winter 2004-5 (averages)**	0.73m	0.51m	0.11m		complete season
		A/ depth 0.73m, 0.51m & 11cm	ST1-1974, ST1-1977, ST1-1	top profile (1.89m)	12.57	12.61	12.78		
		B/ height, 0.63m, 1.26m & 1.89m from floor	ST1-1964, ST1-1963, ST1-1	middle profile (1.26m)	13.40	13.38	13.21		
				low profile (0.63m)	13.71	13.65	13.44		
	Nest Walls	9 sensors buried in a grid at depths / heights	ST1-1965, ST1-1973, ST1-1	**Spring 2005 (averages)**	0.73m	0.51m	0.11m		incomplete season (20 Mar - 20 May)
		A/ depth 0.73m, 0.51m & 11cm	ST1-1974, ST1-1977, ST1-1	top profile (1.89m)	14.64	15.16	15.91		
		B/ height, 0.63m, 1.26m & 1.89m from floor	ST1-1964, ST1-1963, ST1-1	middle profile (1.26m)	15.07	15.59	16.48		
				low profile (0.63m)	14.59	14.63	15.99		
External conditions	External Air Temperature	external weather station	AT2-77	Autumn 2004	6.4	13.32	-0.75	14.07	incomplete season (04 Nov - 21 Dec)
				Winter 2004-5	5.12	18.34	-5.78	24.12	complete season
				Spring 2005	9.48	21.25	-2.56	23.81	incomplete season (20 Mar - 20 May)
				Summer 2005					*data collection ongoing*
	External Solar Radiation	external weather station	GS1-F238	Autumn 2004	0.02	0.33	-0.004	0.34	incomplete season (04 Nov - 21 Dec)
				Winter 2004-5 kW m2	0.04	0.61	-0.004	0.61	complete season
				Spring 2005	0.12	0.86	-0.003	0.86	incomplete season (20 Mar - 20 May)
				Summer 2005					*data collection ongoing*
	External soil temperature	external weather station	ST1-2025	Autumn 2004	11.16	13.07	9.52	3.55	incomplete season (04 Nov - 21 Dec)
		at depth of 15-20cm from top end of the probe		Winter 2004-5	8.13	9.52	6.61	2.91	complete season
				Spring 2005	9.73	11.09	7.46	3.63	incomplete season (20 Mar - 20 May)
				Summer 2005					*data collection ongoing*

Table 2: Monthly summary of data from Earthship and descriptive statistics (all channels) (continued overleaf).

	Sensor type / information	Exact Location	Sensor Reference	Month	Average (°C unless stated)	Maximum (°C unless stated)	Minimum (°C unless stated)	Range (°C unless stated)	Comment
Sensor area	**Sensor Information**			**Summary statistics by month**					green = complete month recorded
Internal temperature and humidity	Radiant Temperature (black globe)	nest	AG-U (30)	Nov-04					*no sensor, installation Feb 21st 2005*
				Dec-04					*no sensor, installation Feb 21st 2005*
				Jan-05					*no sensor, installation Feb 21st 2005*
				Feb-05	13.07	16.63	11.44	5.19	incomplete month (21 Feb-28 Feb)
				Mar-05	14.07	21.19	11.09	10.1	complete month
				Apr-05	16.71	22.28	13.65	8.63	complete month
				May-05	18.39	22.94	16.04	6.9	incomplete month (01 May- 20 May)
				Jun-05					incomplete month (data from 23 June-30th June only): data analysis not performed
				Jul-05					*data collection ongoing*
	Surface temperature	hut	AT2-78	Nov-04					*no sensor, installation 03 Feb 2005*
				Dec-04					*no sensor, installation 03 Feb 2006*
				Jan-05					*no sensor, installation 03 Feb 2007*
				Feb-05	11.58	15.46	11.68	3.78	incomplete month (03 Feb-28 Feb)
				Mar-05	14.13	19.03	11.19	7.84	complete month
				Apr-05	17.52	21.43	14.77	6.66	complete month
				May-05	19.35	23.24	17.07	6.17	incomplete month (01 May- 20 May)
				Jun-05					incomplete month (data from 23 June-30th June only): data analysis not performed
				Jul-05					*data collection ongoing*
	Suface temperature	nest	AT2-81	Nov-04					*no sensor, installation 03 Feb 2005*
				Dec-04					*no sensor, installation 03 Feb 2006*
				Jan-05					*no sensor, installation 03 Feb 2007*
				Feb-05	13.16	15.18	12.23	2.95	incomplete month (03 Feb-28 Feb)
				Mar-05	13.42	17.24	11.91	5.33	complete month
				Apr-05	16.5	21.55	14.24	7.31	complete month
				May-05	18.6	23.48	15.97	7.51	incomplete month (01 May- 20 May)
				Jun-05					incomplete month (data from 23 June-30th June only): data analysis not performed
				Jul-05					*data collection ongoing*
	Air Temperature	hut	AT2-78	Nov-04					SENSOR MALFUNCTION: DISCOUNT
			AT2-78	Dec-04	12.39	16.39	10.60	5.79	complete month
			AT2-78	Jan-05	12.86	19.37	11.12	8.25	complete month
			AT2-78 / Dickson 04366241	Feb-05	12.62	17.83	10.44	7.39	incomplete month, missing data from 03 Feb to 21st Feb
			Dickson 04366241	Mar-05	14.24	24.56	9.89	14.67	complete month
			Dickson 04366241	Apr-05	17.78	25.60	13.60	12.00	complete month
			Dickson 04366241	May-05	20.80	29.60	16.90	12.70	complete month
			Dickson 04366241	Jun-05	22.64	29.40	18.40	11.00	complete month
			Dickson 04366241	Jul-05					*data collection ongoing*
	Air Temperature	nest	AT2-81	Nov-04	14.89	35.92	13.20	22.72	complete month
			AT2-81	Dec-04	12.98	17.73	10.64	7.09	complete month
			AT2-81	Jan-05	12.64	19.61	11.34	8.27	complete month
			AT2-81 /Dickson 04366224	Feb-05	13.07	16.44	11.39	5.06	incomplete month, missing data from 03 Feb to 21st Feb
			Dickson 04366224	Mar-05	14.14	21.39	10.89	10.50	complete month
			Dickson 04366224	Apr-05	16.84	22.10	13.70	8.40	complete month
			Dickson 04366224	May-05	18.94	24.50	16.20	8.30	complete month
			Dickson 04366224	Jun-05	21.71	27.50	18.00	9.50	complete month
			Dickson 04366224	Jul-05					*data collection ongoing*
	Air Temperature	conservatory	AT2-80	Nov-04	15.09	25.26	12.00	13.26	incomplete month (04 Nov -30 Nov)
				Dec-04	6.59	21.40	9.03	12.37	complete month
				Jan-05	13.21	22.49	11.18	11.31	complete month
				Feb-05	13.21	20.80	9.57	11.23	complete month
				Mar-05	15.90	28.04	8.78	19.26	complete month
				Apr-05	20.20	29.88	14.48	15.40	complete month
				May-05	22.00	28.87	18.18	10.69	incomplete month (01 May- 20 May)
				Jun-05					incomplete month (data from 23 June-30th June only): data analysis not performed
				Jul-05					*data collection ongoing*
	Air Temperature	in between trombe wall conservatory	AT2-79	Nov-04	15.33	28.96	10.80	18.16	incomplete month (04 Nov -30 Nov)
				Dec-04	12.99	24.20	10.53	13.67	complete month
				Jan-05	13.57	29.00	9.37	19.63	complete month
				Feb-05	13.76	29.57	10.80	18.77	complete month
				Mar-05	15.24	30.98	10.57	20.41	complete month
				Apr-05	18.59	31.33	12.48	18.85	complete month
				May-05	20.25	29.74	16.23	13.51	incomplete month (01 May- 20 May)
				Jun-05					incomplete month (data from 23 June-30th June only): data analysis not performed
				Jul-05					*data collection ongoing*
	Relative humidity	Nest	Dickson 04366224	Nov-04					*no sensor installation Feb 21st 2005*
				Dec-04					*no sensor installation Feb 21st 2006*
				Jan-05					*no sensor installation Feb 21st 2007*
				Feb-05	59.90740394	61.6	51.2	10.4	incomplete month (21 Feb-28 Feb)
			% RH	Mar-05	62.69270982	69.7	55.6	14.1	complete month
				Apr-05	64.68722467	72.3	38.5	33.8	complete month
				May-05	66.41344387	79.7	48.8	30.9	complete month
				Jun-05	72.32921296	82.4	56	26.4	complete month
				Jul-05					*data collection ongoing*
	Relative humidity	Hut	Dickson 04366241	Nov-04					*no sensor installation Feb 21st 2005*
				Dec-04					*no sensor installation Feb 21st 2006*
				Jan-05					*no sensor installation Feb 21st 2007*
				Feb-05	57.16	61.00	53.20	7.80	incomplete month (21 Feb-28 Feb)
			% RH	Mar-05	61.51	68.20	51.50	16.70	complete month
				Apr-05	60.67	69.70	42.30	27.40	complete month
				May-05	62.40	73.10	43.10	30.00	complete month
				Jun-05	68.47	76.70	53.90	22.80	complete month
				Jul-05					*data collection ongoing*

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Temperatures of Earth Sheltered Mass	Nest Floor	Nest (1 metre from back wall)	ST11989	Nov-04	15.44	17.33	14.46	2.87	incomplete month (04 Nov -30 Nov)
		approx 40 cm deep		Dec-04	13.53	14.93	12.71	2.22	complete month
				Jan-05	13.35	13.99	12.95	1.04	complete month
				Feb-05	13.14	13.64	12.75	0.89	complete month
				Mar-05	13.58	14.95	12.50	2.45	complete month
				Apr-05	15.34	16.39	14.20	2.19	complete month
				May-05	16.81	17.17	16.35	0.82	incomplete month (01 May- 20 May)
				Jun-05					incomplete month (data from 23 June-30th June only): data analysis not performed
				Jul-05					
	Nest Floor	Nest (1 metre from nest planter)	ST1990	Nov-04	15.60	17.52	14.56	2.96	incomplete month (04 Nov -30 Nov)
		approx 40cm deep		Dec-04	13.40	14.66	12.47	2.19	complete month
				Jan-05	13.08	13.58	12.77	0.81	complete month
				Feb-05	13.03	13.75	12.58	1.17	complete month
				Mar-05	13.55	14.97	12.36	2.61	complete month
				Apr-05	15.36	16.44	14.16	2.28	complete month
				May-05	16.88	17.21	16.37	0.84	incomplete month (01 May- 20 May)
				Jun-05					incomplete month (data from 23 June-30th June only): data analysis not performed
				Jul-05					
	Kitchen Walls	9 sensors buried in a grid at depths / height	ST1-1966, ST1-1988, ST1-1968						
		A/ depth, 0.79m,0. 51m & 0.25m	ST1-1967, ST1-1969. ST1-1970						
		B/ height, 0.63m, 1.26m & 1.89m from floor	ST1-1971, ST1-1986, ST1-1987						
	Kitchen Walls	9 sensors buried in a grid at depths / height	ST1-1966, ST1-1988, ST1-1968						
		A/ depth, 0.79m,0. 51m & 0.25m	ST1-1967, ST1-1969. ST1-1970						
		B/ height, 0.63m, 1.26m & 1.89m from floor	ST1-1971, ST1-1986, ST1-1987						
	Kitchen Walls	9 sensors buried in a grid at depths / height	ST1-1966, ST1-1988, ST1-1968						
		A/ depth, 0.79m,0. 51m & 0.25m	ST1-1967, ST1-1969. ST1-1970						
		B/ height, 0.63m, 1.26m & 1.89m from floor	ST1-1971, ST1-1986, ST1-1987						
									data only analysed by season (change less rapid than to warrant data analysis by month)
	Nest Walls	9 sensors buried in a grid at depths / height	ST1-1965, ST1-1973, ST1-1972						
		A/ depth 0.73m, 0.51m & 11cm	ST1-1974, ST1-1977, ST1-1976						
		B/ height, 0.63m, 1.26m & 1.89m from floor	ST1-1964, ST1-1963, ST1-1975						
	Nest Walls	9 sensors buried in a grid at depths / height	ST1-1965, ST1-1973, ST1-1972						
		A/ depth 0.73m, 0.51m & 11cm	ST1-1974, ST1-1977, ST1-1976						
		B/ height, 0.63m, 1.26m & 1.89m from floor	ST1-1964, ST1-1963, ST1-1975						
	Nest Walls	9 sensors buried in a grid at depths / height	ST1-1965, ST1-1973, ST1-1972						
		A/ depth 0.73m, 0.51m & 11cm	ST1-1974, ST1-1977, ST1-1976						
		B/ height, 0.63m, 1.26m & 1.89m from floor	ST1-1964, ST1-1963, ST1-1975						
External conditions	External Air Temperature	external weather station	AT2-77	Nov-04	7.31	13.32	-0.66	13.98	incomplete month (04 Nov -30 Nov)
				Dec-04	5.65	12.16	-2.72	14.88	complete month
				Jan-05	6.27	11.75	-1.19	12.94	complete month
				Feb-05	3.95	12.77	-5.78	18.55	complete month
				Mar-05	6.40	18.34	-5.51	23.85	complete month
				Apr-05	9.05	21.04	-2.56	23.60	complete month
				May-05	10.14	21.25	1.74	19.51	incomplete month (01 May- 20 May)
				Jun-05					incomplete month (data from 23 June-30th June only): data analysis not performed
				Jul-05					*data collection ongoing*
	External Solar Radiation	external weather station	GS1-F238	Nov-04	0.023	0.335	-0.004	0.339	incomplete month (04 Nov -30 Nov)
				Dec-04	0.017	-0.002	-0.003	0.001	complete month
				Jan-05	0.023	0.358	-0.003	0.362	complete month
				Feb-05	0.043	0.512	0.000	0.512	complete month
			kW m2	Mar-05	0.067	0.640	-0.004	0.645	complete month
				Apr-05	0.115	0.811	-0.003	0.814	complete month
				May-05	0.146	0.861	-0.001	0.862	incomplete month (01 May- 20 May)
				Jun-05					incomplete month (data from 23 June-30th June only): data analysis not performed
				Jul-05					*data collection ongoing*
	External soil temperature	external weather station	ST1-2025	Nov-04	11.91	13.07	11.12	1.95	incomplete month (04 Nov -30 Nov)
		at depth of 15-20cm from top end of the probe		Dec-04	9.80	11.12	8.51	2.61	complete month
				Jan-05	8.62	9.04	7.98	1.06	complete month
				Feb-05	8.09	8.48	7.32	1.16	complete month
				Mar-05	7.47	8.96	6.61	2.35	complete month
				Apr-05	9.52	10.12	8.95	1.17	complete month
				May-05	10.87	11.09	10.12	0.97	incomplete month (01 May- 20 May)
				Jun-05					incomplete month (data from 23 June-30th June only): data analysis not performed
				Jul-05					*data collection ongoing*

K/ Discussion

Raw data has been manipulated into Excel and examined largely in the continuous periods of data available for all sensors in winter 2004-5 and summer 2005. Each element which has been selected for analysis /discussion is covered separately below.

Ki/ The Earth sheltered Wall and Influence on Internal Environment

To examine how the earth sheltered walls respond to the external environment during different seasons is necessary.

Profiles for the ESRW in the kitchen and the nest modules are shown in the following two sets of graphs.

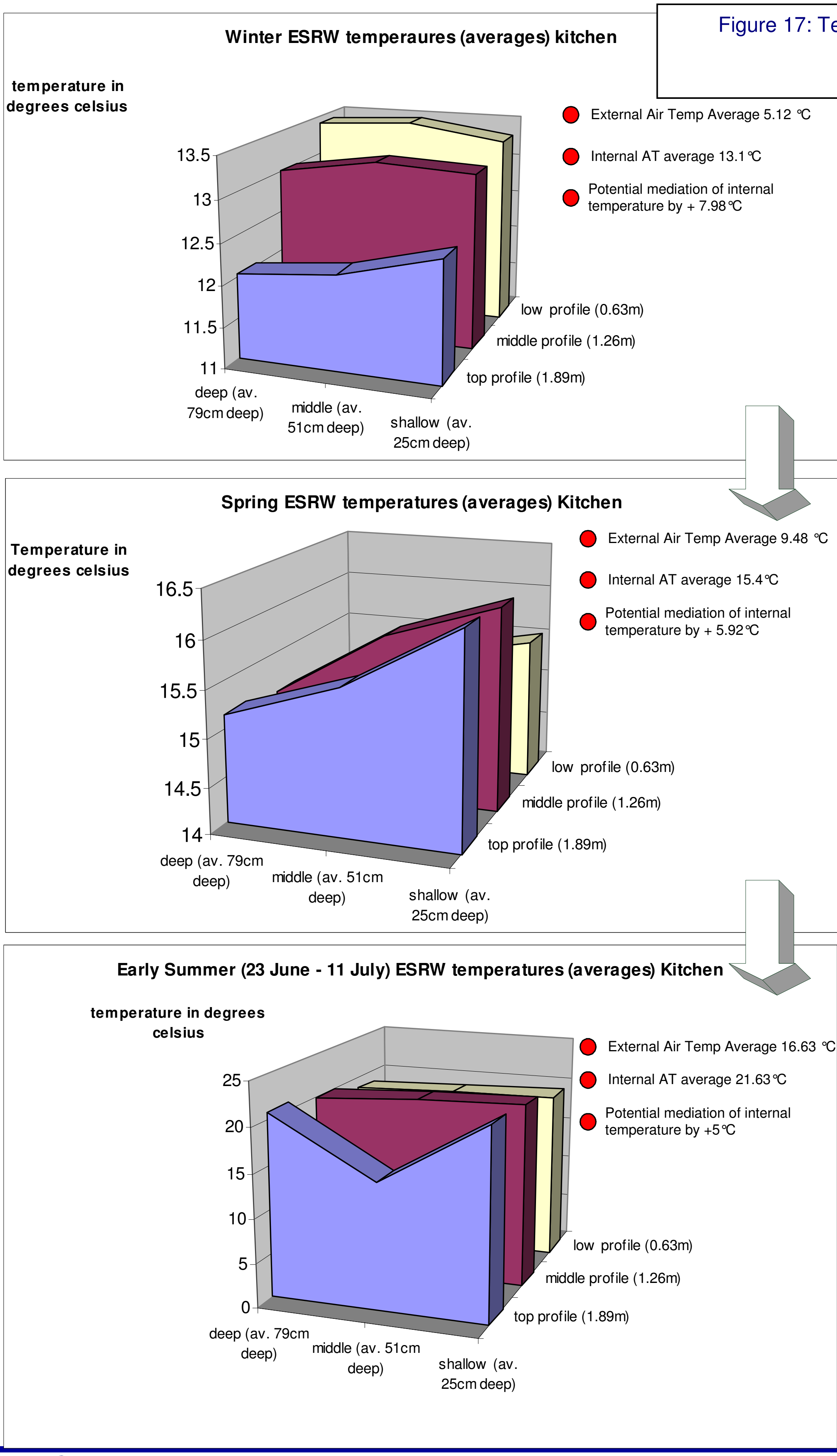
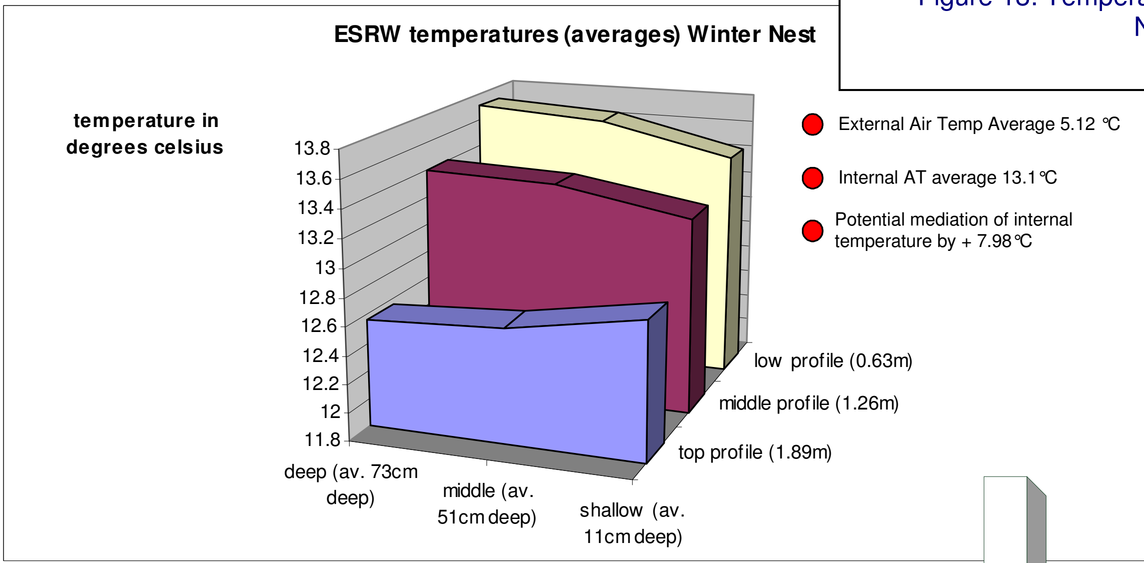
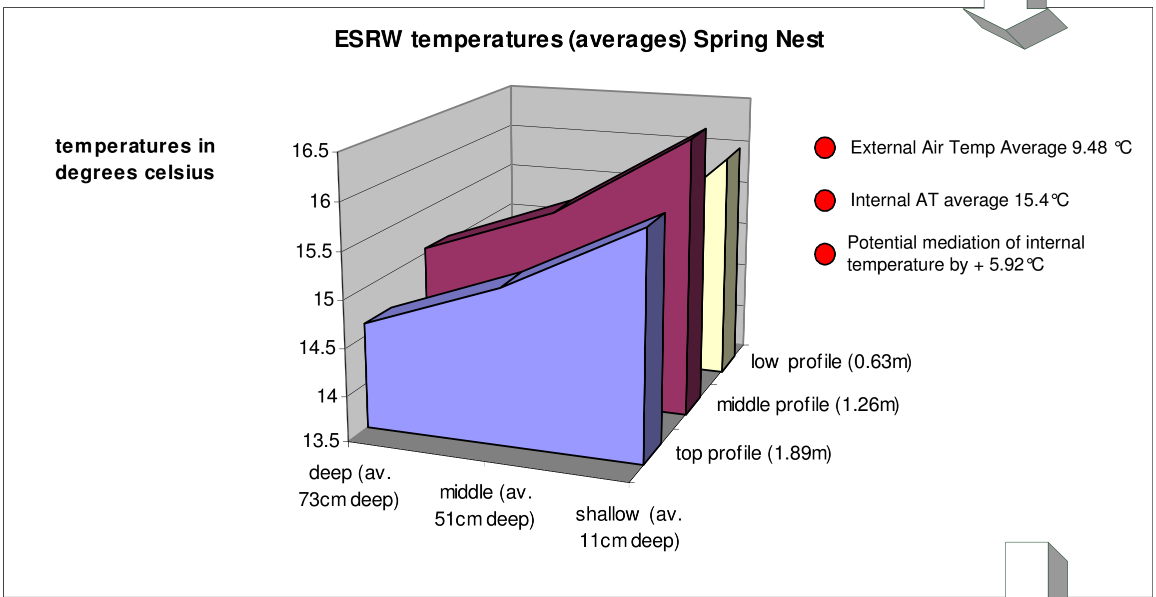
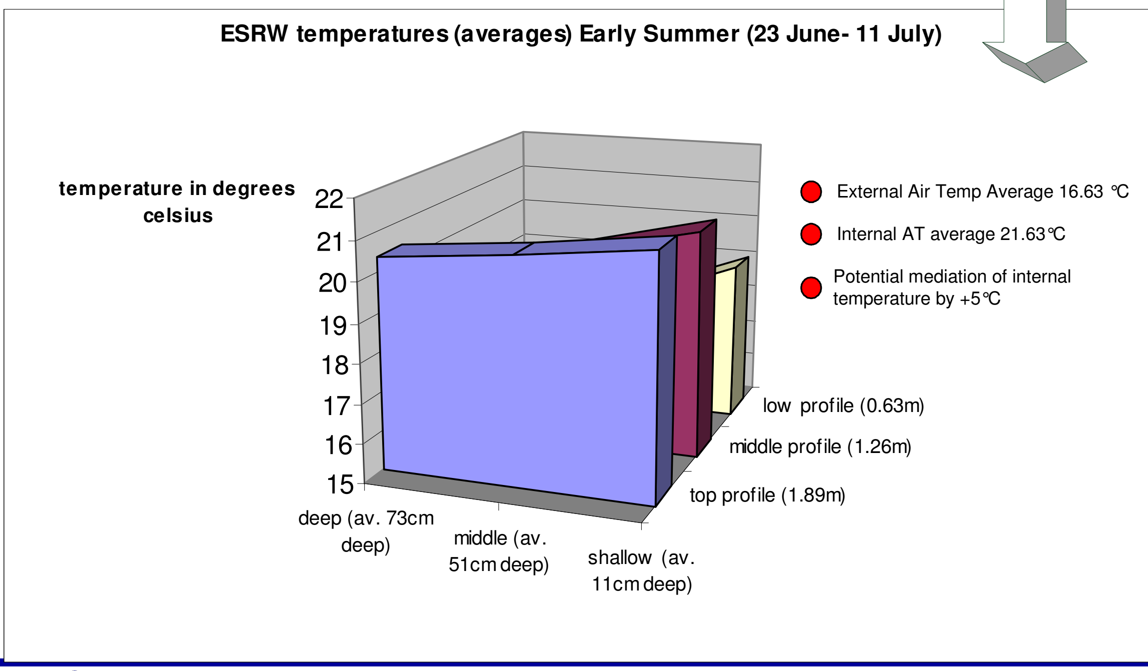


Figure 17: Temperatures in the Kitchen ESRW.

Figure 18: Temperatures in the Nest ESRW.







There are a number of observations and comments which can be drawn from these graphs.

- Both sets of graphs from the kitchen ESRW and the nest ESRW display very similar profiles despite there being a slightly thicker element of earth sheltering behind the nest wall.
- The temperature of the ESRW at all sensor positions is higher in the summer, than the spring, and in the spring than the winter.
- The profile of which part of the nine sensor grid is the warmest during each season does change however and some differences are displayed between the nest and the kitchen. In the Kitchen ESRW during the winter temperatures peak within the middle of the ESRW measurement grid whereas in the nest the peak (by a very small margin) is at the deepest sensor. This is potentially due to the aforementioned slightly thicker earth sheltering of the nest wall when the grid of sensors are in very similar positions on both walls.
- In winter the only profile which becomes warmer the closer to the internal surface of the wall is the top profile (at a height of 1.89m from the internal floor) in both the nest and the kitchen. It is possible this is due to the influence of the internal temperature of building peaking near the ceiling due to natural convection and influencing the shallowest of the sensors.
- Overall the difference between the three height profiles in each set of three graphs becomes less varied during the spring and the summer. As the external temperature moves towards a more comfortable average the temperature stratification in the sensor grid appears to be less pronounced.
- The dip in temperature in the middle sensor of the top profile in the kitchen ESRW during the summer is unexplained. However, one potential explanation is the composite nature of the walls (tyres, rammed earth, glass and aluminium) may mean that it cannot be guaranteed that this sensor is not in contact with one element of the wall which may behave differently to others when subjected to different external temperatures.

Furthermore, provided with the graphs in Figures 17 & 18 is the average external air temperature for the season / data period in question and the average internal air temperature. The difference between these figures is also given although it would be unwise to assume that this difference (which is always warmer than the external average) is entirely due to the effect of the ESRW as opposed to the effect of any sealed unit of construction (e.g. garden shed, standard housing construction etc.) upon internal temperatures. Furthermore, research to be undertaken by Durabuild to ascertain more precisely the way in which the ESRW may be acting as a heat source in winter and a heat sink in summer will take advantage of a longer period of data collection and employ specialist software. This software (Physibel) will allow the modelling of the ESRW in more detail by being able to specify its composite nature in more detail and determine the nature of heat transfer through it, whereas more generic modelling software which works using wider elements of building fabric requires each composite to be specified as a separate layer.

Previous modelling using the IES Virtual Environment 5.2.0 (IESEVE) software (a suite of linked modelling components which can be used for predicting building performance) by Ip et al (2005) simulated the effect on internal temperatures which different internal temperatures in the ESRW would have. The results were simulated for a week in December (external air temperatures constant in each simulation at the Gatwick dataset of 12.5℃ maximum and 6.5℃ minimum). It was offered by Ip et al (2005) that not only do the maximum and minimum resultant air temperatures increase significantly with the increase in ESRW temperatures but that the measured data for this period is higher (17.73℃ maximum and 10.85℃ minimum, average 14.29℃) These results are shown below and would suggest indeed that looking at the behaviour of the wall in more detail using measured data may be able to provide insight into the factors which may be increasing the internal temperatures over that expected by modelling, or indeed reassess any difference in the results should the new model using Physibel be more characteristic than the existing simpler IESVE model.

	Earth sheltered rear wall (ESRW) temp.		
Simulation parameter	**0℃**	**10℃**	**15℃**
Air temp max	9℃	12.5℃	14.5℃
Air temp min	1℃	5℃	7℃
Range	*8℃*	*7.5℃*	*7.5℃*

Table 3: Results from simulation of internal air temperatures for different wall temperatures (Ip et al, 2005).

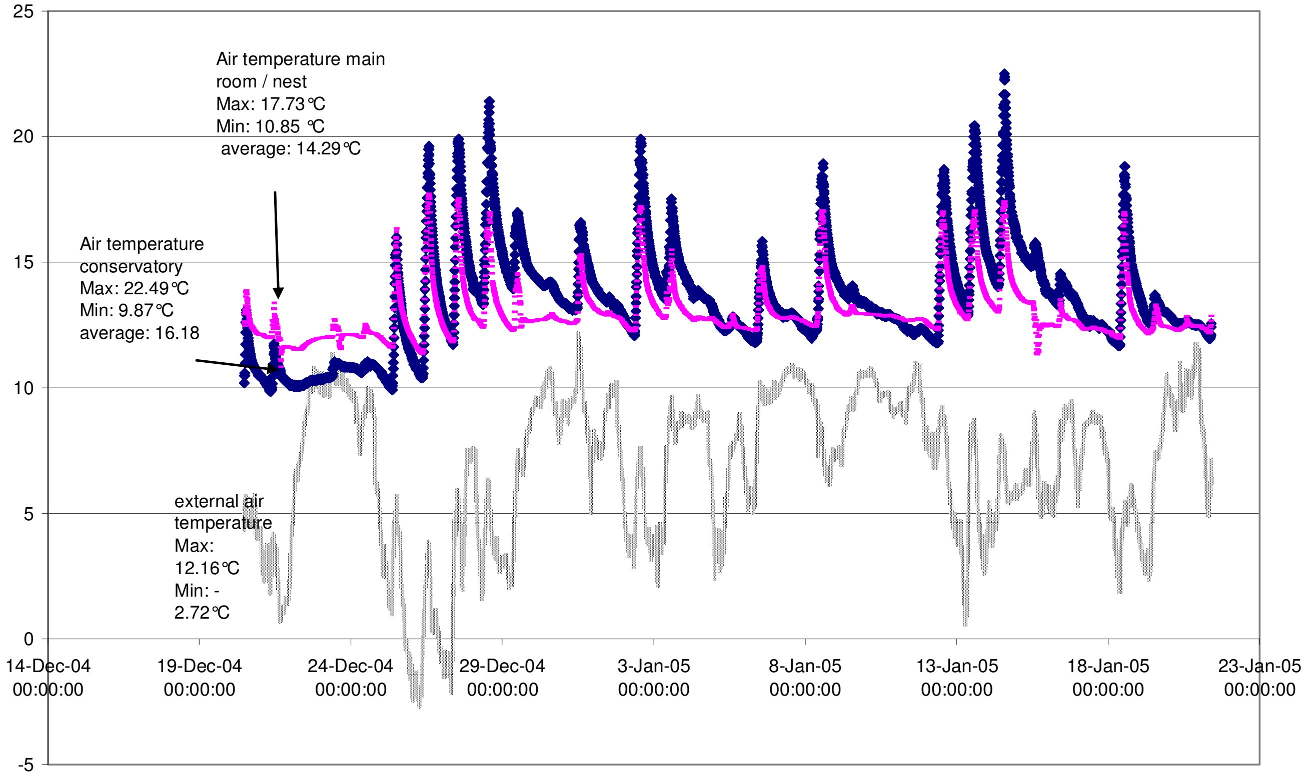


Figure 19: Recorded data for internal and external air temperature (Dec 20th –Jan 20th 2004).

Kii/ Internal Environment and Thermal Comfort within the Earthship.

Human bodies produce heat through ingestion and digestion of food and lose heat to the environment at different rates dependent on activity. This loss of heat is part of the thermo-regulatory system of the human body which attempts to maintain a constant balance of around 37 degrees celsius through actions such as sweating when too hot and shivering when too cold. This maintenance is achievable of a scale which is wider than the scale of thermal comfort i.e. you may feel hot and uncomfortable after exercise, or sat in an office experiencing excessive solar gain but your deep body temperature will remain around 37 °C (CIBSE, 2004)

Four main environmental factors in combination influence the sensation of thermal comfort, or discomfort (although other factors have an influence e.g. clothing and contact with other materials such as lying on a sofa) (CIBSE, 2004) these are defined as follows

1. **Air temperature:** (in °C) t_a

2. **Mean radiant temperature (globe):** within an environment (in °C) t_r is defined as the uniform temperature of an imaginary black globe enclosure which would experience the same heat loss by radiation (heat transfer without the presence of a medium) as a person within the same environment (Innova, 2002). Because the amount of radiation emitted by an object depends on its temperature and surface quality / colour the equation for the calculation of t_r takes into account surface temperature. However to measure all surface temperatures and related angle factors in an environment (e.g. slope of ceilings) is a very laborious task, other working definitions have been adopted (see further explanation below).

3. **Relative humidity:** (% RH) describes the amount of water in the air compared with how much the air can hold at the current temperature. Example: 50% relative humidity means the air holds half the water vapour that it is capable of holding; 100% relative humidity means the air holds all the water vapour it can. At 100% humidity, no more evaporation can occur until the temperature rises, or until the water vapour leaves the air through condensation (Vann, 2005)

4. **Relative air speed:** in m/s

Essentially, the human body does not feel the room temperature but the sensation of energy being lost from the body, the four environmental factors given above are those which influence bodily heat loss and therefore require measurement to assess thermal comfort when monitoring indoor climate conditions.

In order to address the range of parameters and avoid the potential time consuming calculation aforementioned for such parameters as mean radiant temperature industry bodies and professionals such as CIBSE (Chartered Institution of Building Services Engineers) and ASHRAE (American

Society of Heating Refrigeration and Air Conditioning Engineers) have settled on a single working definition for temperature conditions surrounding thermal comfort (humidity is treated separately in its own right). There are a range of thermal indices, some for extreme conditions however, the integrating index of dry resultant temperature t_c (combining air and mean radiant temperatures) is most commonly used.

This is expressed in the following equation

$$t_c = \frac{t_{ai}\sqrt{(10v)} + t_r}{1 + \sqrt{(10v)}}$$

t_c dry resultant temperature in °C
t_{ai} inside air temperature in °C
$t_{r:}$ mean radiant temperature in °C
v air speed (m/s)

Air speeds within the Earthship are assumed to be very low as the main room is separated from external conditions by a conservatory and the earth sheltering on both sides. CIBSE therefore recommend that when the air speeds are below 0.1 m/s that the equation can be simplified to the following

$$t_c = 0.5t_{ai} + 0.5t_r$$

When assessing the thermal comfort performance of the Earthship to link the results back to standards / recommended design criteria is essential. An Earthships usual intended use is a dwelling, however, in Brighton the living area (nest module) is likely to be used as a seminar room, and the hut as an office, the recommended relevant comfort criteria parameters (CIBSE 1999) are as follows:

- living room of a dwelling (22-23°C in winter and 23-25°C in summer)
- offices (executive, general, or open plan) (21-23°C in winter and 22-24 °C in summer)
- seminar rooms (19-21°C in winter and 21-23°C in summer)

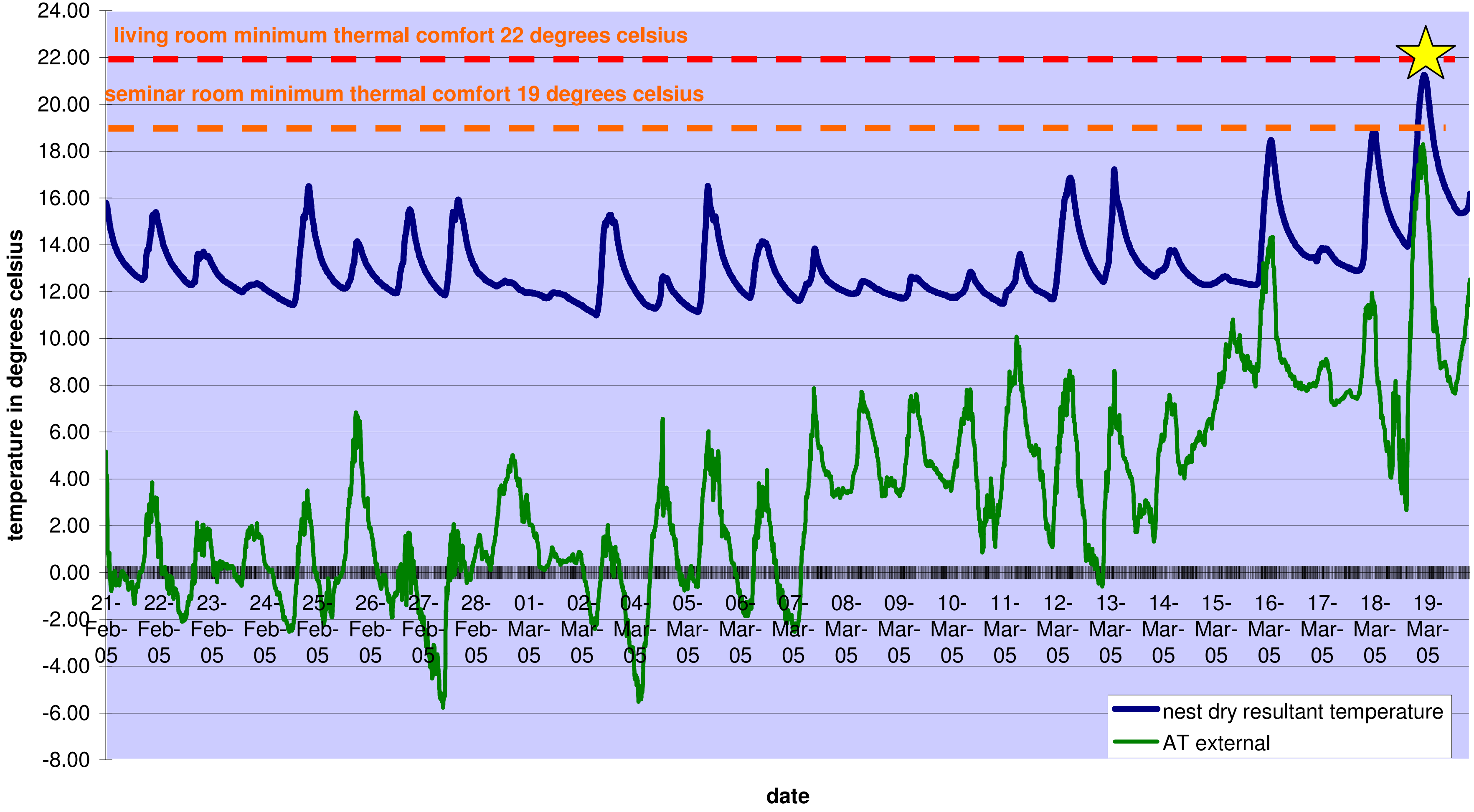
Analysing the data from sensors within the Earthship to assess thermal comfort expressed in dry resultant temperature can be done accurately using this method only for the main room / nest as although other modules of the building have air temperature sensors, they do not have black globe sensors. The black globe sensor was installed after the majority of other sensors on February 21st, meaning that only a proportion of the entire winter season is available for analysis on this level (the entire season which runs from 21 December 12.41 pm 2004 to 20 March 12.33pm 2005). Therefore the analysis for the winter data to be compared to winter thermal comfort standards is for the period of 22nd February 2005 to 19 March 2005 (first and last whole days of data during this period).

Data analysis reveals it is essentially the case that there is little difference in the final figures when calculating the resultant dry temperature t_c from the two input factors of air temperature t_{ai} and black globe temperature t_r. The maximum difference in these readings being 1.02 °C and the average difference in the values in the data set being 0.01°C over the period February 21st – March 20th. Nevertheless, the ability to undertake these calculations with data from the nest allows an element of confidence when using standard air temperature t_{ai} readings from other areas within the Earthship (sensors located within conservatory and hut module).

The following graph shows the results of the dry resultant temperature t_c within the nest module from the aforementioned period. It is immediately apparent that the comfort temperature for either of the proposed uses of this module of the building (living room, or seminar room) is not being met during the winter months. Only on one day (19th March 2005 between 11.24am and 17.54 am, marked by the yellow star) does the dry resultant temperature t_c exceed the minimum thermal comfort for a seminar room.

The external air temperature on the graph can be seen to suggest that there is positive response to these winter peaks in external air temperature whereas there is a relatively stable temperature of around 13°C during the periods of most extreme low temperatures experienced during February 2005. This is potentially due to the activity of the thermal storage and transfer from the ESRW in moderating the external fluctuations in temperature, a main principle of Earthship design. This will be discussed more fully when examining the data collected from the sensors buried in the ESRW in subsequent sections.

Figure 20: Dry resultant temperature, external air temperature and thermal comfort in the nest module (Winter 2005).

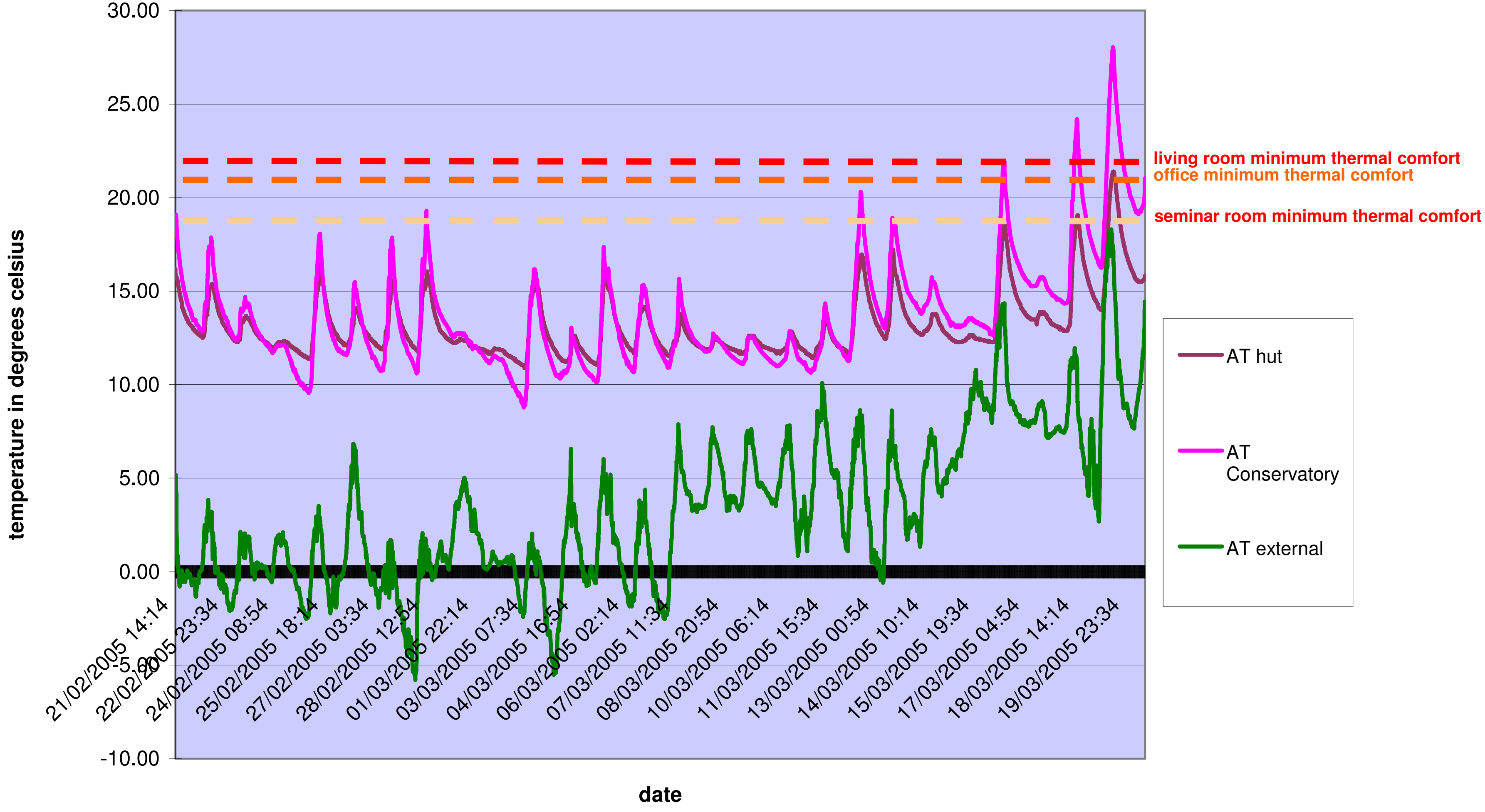


In order to look at other modules of the Earthship over the same winter period, the data for standard air temperature is used as the only mean radiant temperature (globe sensor) is located within the nest module. Figure 18 shows conditions within the hut and the conservatory. As the hut has a different intended use as an office, the minimum thermal comfort level for this is also shown.

Only the conservatory module on occasion exceeds thermal comfort levels, although this is unsurprising as it is designed to trap sunlight for the botanical planter cells which will be present in the completed building and also to act as a buffer for the main living area against excessive solar gain. Accordingly the conservatory with the large glazed area also loses heat to a greater degree than the hut module when the external temperature drops.

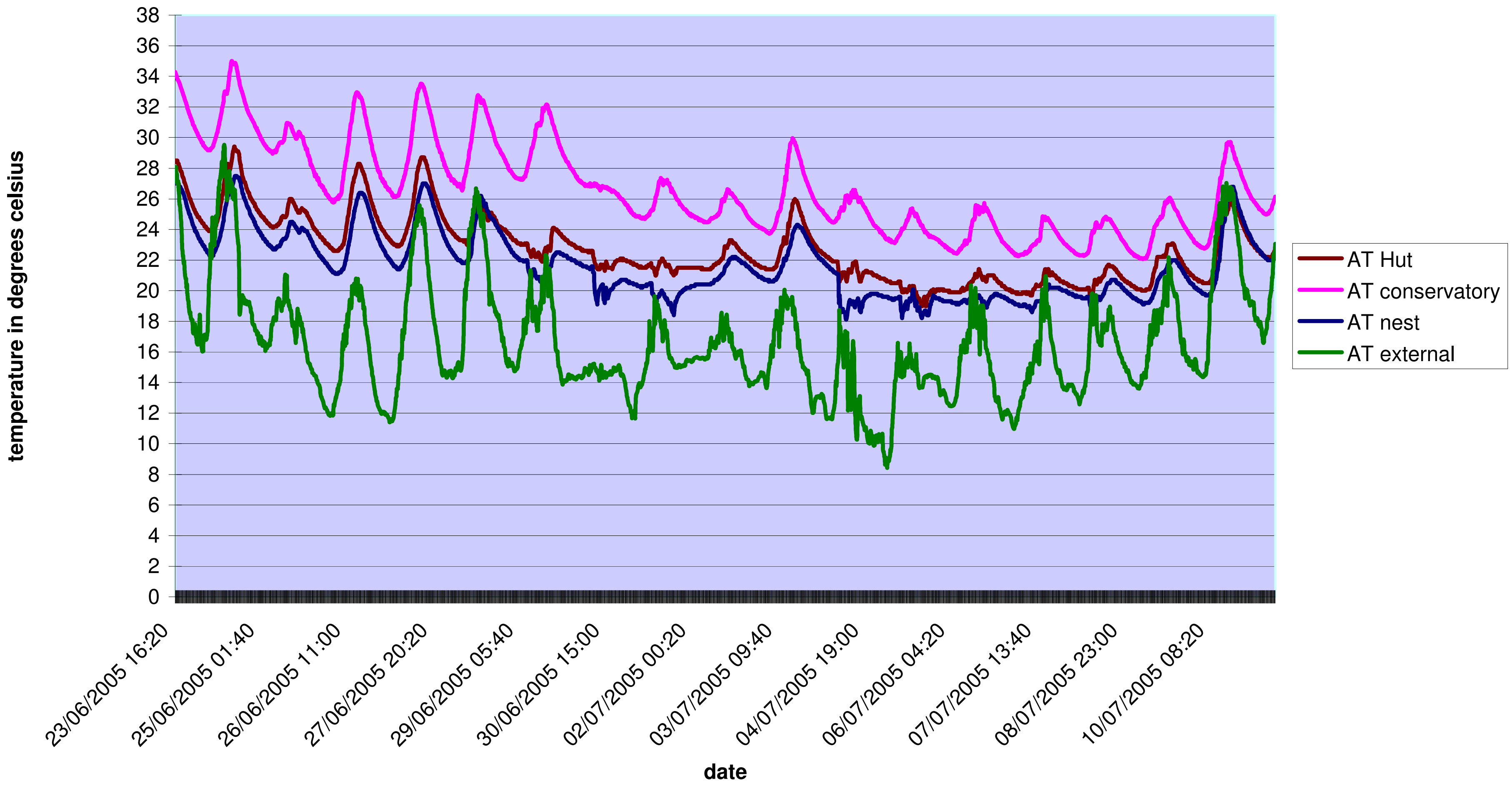
Although separate thermal elements, both the hut and the nest modules appear to be experiencing similar internal climate conditions. This situation may however change with the completion of the building as there are no internal doors at present (only plastic sheeting) which does not prevent the passage of air both in and out of the end of the conservatory section nearest the hut and the kitchen.

Figure 21: Internal air temperature, external air temperature and thermal comfort in the hut and conservatory (Winter 2005).



To look more widely at the analysis of achievement of thermal comfort, at the time of writing there not a complete collection of data for summer 2005. However, to examine data which is available from 23 June 2005 to July 11th does provide some hints on what may be found for the full season during future analysis. The full profiles are shown in the following graph.

Figure 22: Internal air temperature, external air temperature and thermal comfort in all earthship modules June-July 2005.



The following series of pie charts (Figure 20) and the table below (Table 3) represent the thermal comfort profiles of the different modules of the Earthship and their potential associated uses.

A number of trends and facts of note present themselves.

- The Hut is the most comfortable of the modules (spending most time within the thermal comfort parameters) when assessed as a seminar room. Unfortunately its intended use is as an office and it is too cold for this purpose almost 50% of the time.
- The Conservatory is above thermal comfort for all uses a large amount of the time (over 75% in two instances). This is unsurprising considering the intention is to trap heat in this part of the building and is not intended as dwelling area. Nevertheless, it is useful to have ascertained its profile for comparison with other modules.
- The nest is the coldest of the three modules, spending between approximately half and three quarters of its time being too cold for any of the three potential uses. However, it does perform best for its intended use as a seminar room. It will be interesting to follow the profile of this module (as its the coldest) at the beginning of the summer heating season to see how the profile changes over the remaining summer months and entering the autumn. Over the much longer anticipated two years it takes the internal climate in an Earthship to reach an equilibrium it will also be necessary to examine the longer trends when the data is available.
- The impact of any internal gains when the building is occupied and building user comments if available will also make for interesting analysis.

	Hut	Conservatory	Nest	Average for period (internal temp)	external AT
Comfort (living room Summer min 23, summer max 25)					
below minimum %	59.80	9.69	74.86	22.70°C	91.92%
within range %	23.88	27.22	15.80		3.65%
above maximum %	16.31	63.10	9.33		4.43%
Comfort (office Summer min 22, summer max 24)					
below minimum %	45.45	0.00	59.69	26.62°C	90.55%
within range %	29.10	20.86	24.63		2.94%
above maximum %	25.45	79.14	15.69		6.51 %
Comfort (seminar room Summer min 21, summer max 23)					
below minimum %	23.80	0.00	46.31	21.63°C	89.29%
within range %	38.59	10.21	29.61		2.78%
above maximum %	37.61	89.88	24.08		7.92%

Table 4: Thermal comfort limits in the three Earthiship modules (early Summer 2005).

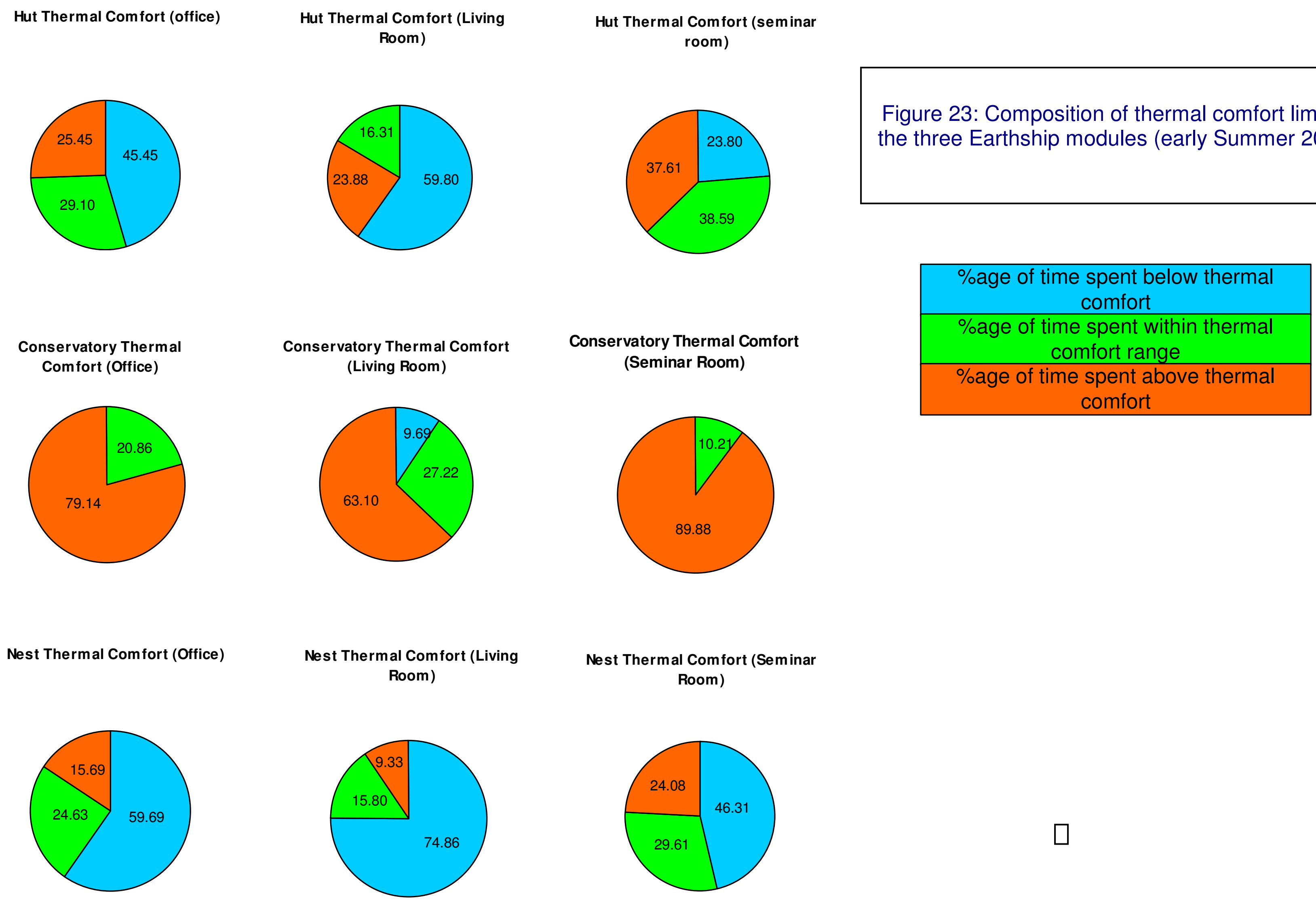


Figure 23: Composition of thermal comfort limits in the three Earthship modules (early Summer 2005).

It is interesting to again compare previous work on Earthships (Grindley & Hutchinson, 1996) with the data collected by Durabuild on the Brighton Earthship. Ip et al in the 2005 paper already note the potential for overheating in the summer and the need for additional heating during the winter.

Hutchinson & Grindley's measured data was from Taos, New Mexico, the original climate for Earthship design. Computer modelling undertaken by both Grindley and Hutchinson (1996) and Ip et al (2005) along with the measured data from the UK does demonstrate an element of overheating in the summer. Grindley & Hutchinson (1996) note the main elements in Earthship shading design are, however, difficult to model in computer simulations. Earthships generally incorporate two large 'planters' (one in the conservatory, and one in the nest module in which plants function primarily as grey and black water treatment cells). These planters provide adjustable shading with pruning (Reynolds 1990) along with blinds.

There is an important parallel with the problems noted by Hutchinson & Grindley (1996); the Brighton Earthship has incomplete planters and no shading devices due to its stage of construction so the periods of overheating noted in the measured data may be tempered somewhat when the building is completed.

The underheating, especially within the nest module is one factor which may be subject to change from internal gains when the building is finished and occupied and its progress will be fully monitored.

Relative humidity is another parameter of thermal comfort within the Brighton Earthship which Durabuild have been monitoring. Although humidity has little effect on feelings of warmth experienced by people (sedentary and wearing light clothing) at dry resultant temperatures of 23°C or below (CIBSE, 1999) it is still valuable to discuss this parameter, especially considering the periods of overheating noted in the monitoring.

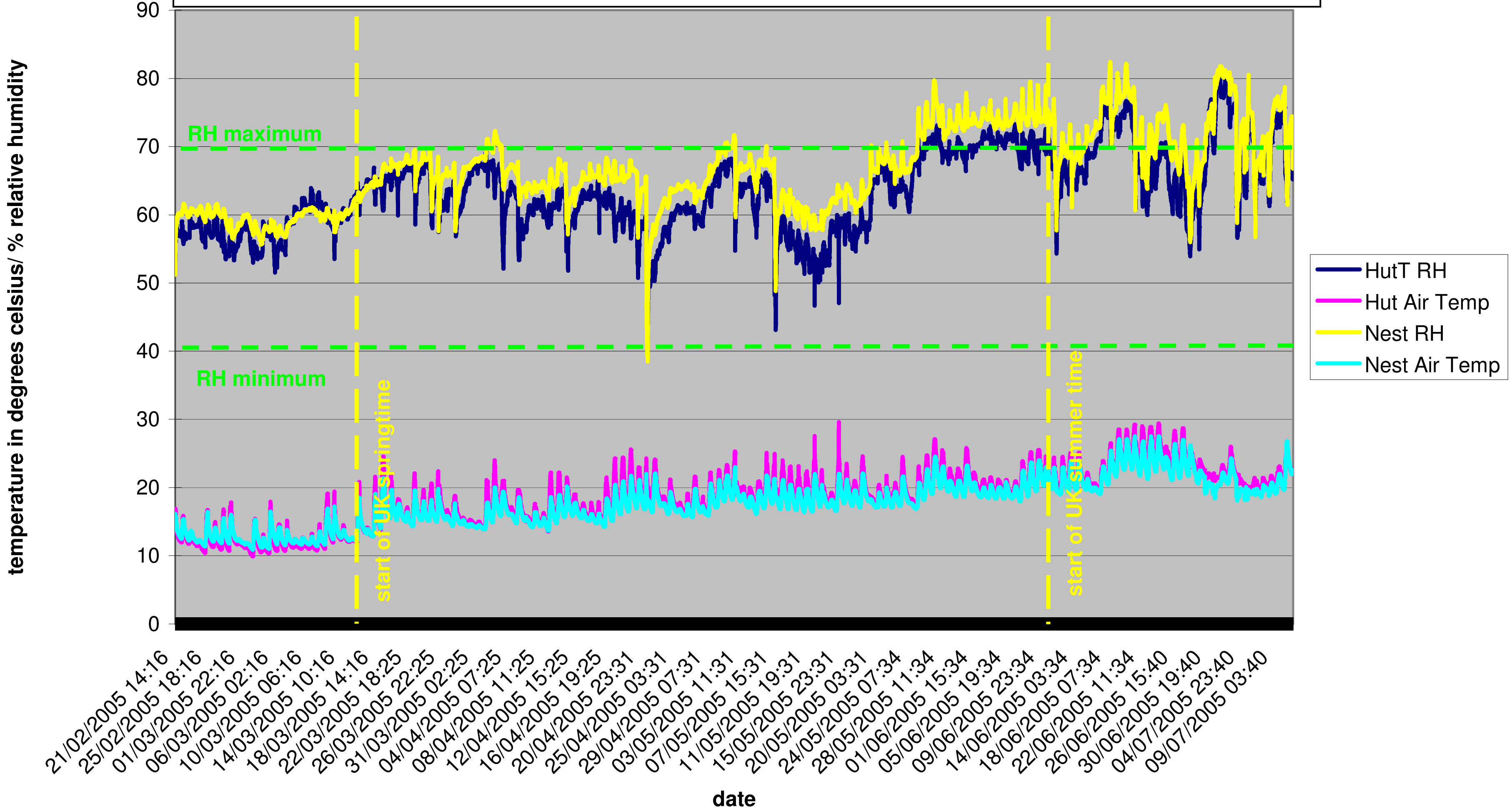
Two readings for relative humidity (RH) are taken, in the hut and the nest, at the same intervals as temperature readings.

The following graph shows the trend in relative humidity experienced in both areas, in the same winter and summer periods as have been used in the discussion so far. The range for relative humidity is quite broad, from 40-70% being acceptable in most situations (CIBSE, 2001).

It is apparent from the graph that during the end of spring the RH begins to exceed the range of comfort. Although this is true for both the hut and nest modules, this is at a higher level within the nest although the temperatures in here are relatively lower than in the hut.

During the period in which the readings were taken the building was unoccupied, however if it were completed and occupied inhabitants experiencing excessive humidity have the option of two large skylight ventilation hatches in the roof of the nest and a large plenum ventilation mechanism in the hut. Once the building is finished and occupied it will be of interest not only to see a longer period of data collection for this parameter but to ascertain if the readings will change in line with any occupant driven ventilation patterns.

Figure 24: Relative humidity and temperature in the hut and nest February 20th to July 11th 2005



Kiii/ The impact of solar radiation

The following graphs show the external solar radiation, internal conservatory and nest temperatures during one week in January and one week in July 2005.

Figure 25: Solar radiation and internal conservatory and nest temperatures January 4th-11th 2005

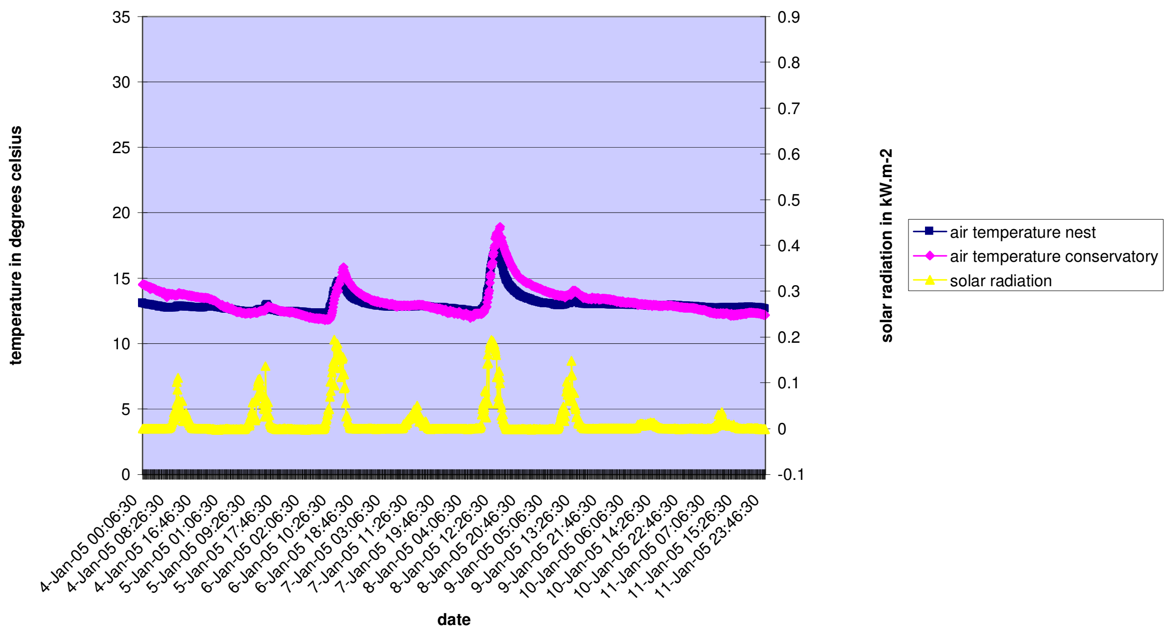
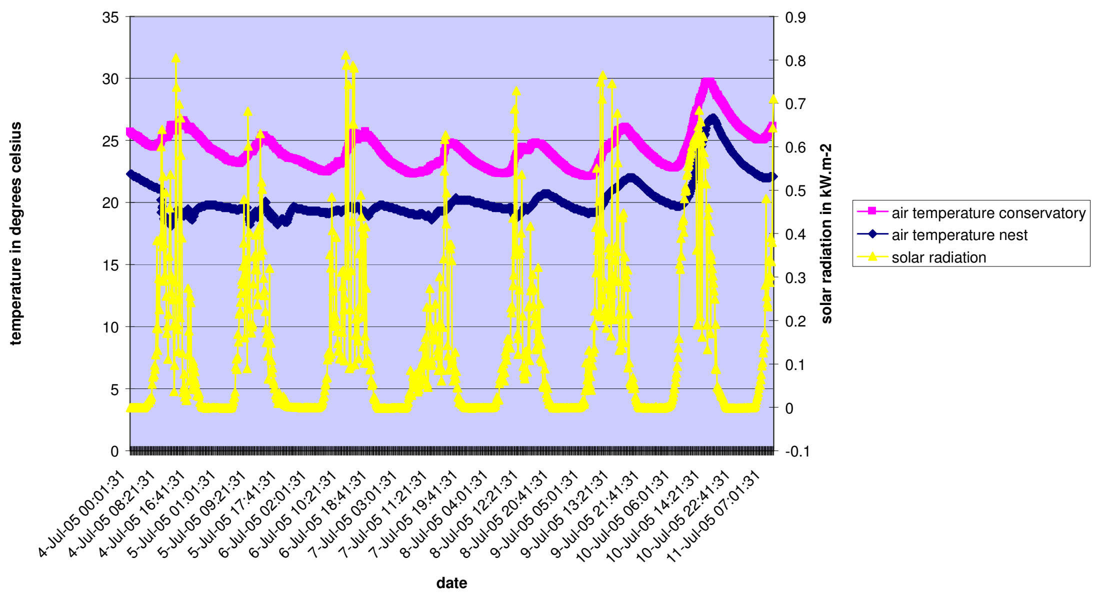


Figure 26: Solar radiation and internal conservatory and nest temperatures July 4th-11th 2005



Both graphs demonstrate peaks in internal temperatures which would be expected to correlate with peaks in external solar radiation. The solar radiation is naturally higher in the summer.

Although there are other factors which will influence internal temperatures such as external air temperatures and the thermal storage affect of the tyre walls, the influence of the deliberate angle of the glass façade on the conservatory (shown earlier in Figure 10) may be shown to some extent in these graphs. With the glass angled at 45° to maximise the winter sun angle and minimise the summer sun angle i.e. make the maximum use of the limited solar gain available in the winter months for heating and control the amount of solar gain in the summer for cooling purposes. The nature of the temperature fluctuations varies between the graphs. The high peaks in solar gain the summertime are accompanied by a more gentle rise and fall of the temperatures in the conservatory and nest than they are in the winter data. This is potentially due to the curtailment of solar radiation into the depth of the building through the angled glass.

The fact that the air temperature differences between the conservatory and the nest are more separated during the data from July than January could also support this theory i.e. solar gain is affecting the conservatory to a far greater degree than the nest. However, this could also be due to the suspected action of the ESRW as a heat sink during this period.

Therefore closer examination of this data, (when more data sets are compared to one another and more complex tests are applied to the pattern of the data), along with the more detailed modelling to be undertaken with specialist software may yield more concrete assertions as to the individual contribution the angle of the glass and associated solar gain from external radiation has on the internal temperature gains.

Conclusions & Future Work

The current report is based on preliminary results before the building is completed or occupied and before a dataset for anentire heating and cooling season has been recorded. However, it is possible to conclude upon the individual tests which have been performed on the data extracted so far, in so far as these must be taken as initial results and potentially not indicative of the buildings final performance.

So far the situation can be summarised as follows. The Brighton Earthship does appear to be moderating the extremes of external temperatures, although these are generally still below thermal comfort conditions for the majority of the time within the main module, the Nest. Periods of overheating are also experienced. However, with no internal gains, and also no permanent shading devices or occupant driven ventilation regimes this is data is likely to be subject to potential significant change once the building is completed and occupied.

Along with assessing longer periods of data to establish whether the building, and certain elements within it such as the ESRW are to enter a state of thermal equilibrium the more detailed modelling of these elements within specialist software packages such as Physibel should provide further insight into the inner workings of the earth sheltered structure at a more *cause* than *effect* level. Deeper investigation into quantifying the actions of the earth sheltering in relation to internal and external conditions as opposed to investigations into its apparent effects upon the internal environment as have been undertaken so far is to form the crux of future work.

Future work will also expand to look at other aspects of the Brighton Earthship not assessed within this monitoring programme. The use and properties of the Eco-crete (carbon emission reduction through production compared to standard cement and carbon sequestration during its lifecycle) used within the tyre walls will be the subject of new research under the CUPP (Community University Partnership Fund) during 2005-6.

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