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Measurement for Innovators – Joint Industry Project 2007_029
Contract number KO001026

Measurements to evaluate the thermal performance of building structures under dynamic temperature conditions

Chris Sanders (Glasgow Caledonian University)
Ray Williams (National Physical Laboratory)
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ABSTRACT

The thermal properties of seven different wall structures, including a conventional brick/cavity/expanded polyurethane (PUR)/Autoclaved Aerated Concrete (AAC) wall, a timber frame wall, a solid AAC wall, a lightweight concrete block wall and three types of Insulating Concrete Formwork (ICF) walls were measured in the NPL Hot Box under both steady state and thermal cycling conditions. From these measurements the following thermal properties were derived: U-value; the energy per 24 hours to sustain a warm side temperature of 23 °C whilst the cold side was cycled from 2.5 °C to 14.5 °C; the amplitude of the resulting power fluctuations; the time lag between the maximum temperature difference and maximum power; and the time lag between the minimum cold side temperature and minimum warm side temperature. Many of these thermal properties were calculated by Glasgow Caledonian University using the Physibel VOLTRA software and some of the U-values were calculated using the methodology specified in BS EN ISO 6946.

The results show that the values of the energy used per 24 hours correlated well with U-value and that the power fluctuations through the ICF walls were lower by a factor of 1.8 than through the conventional brick wall. The agreement between the U-values calculated using VOLTRA and the measured U-values ranged between 5% and 18% with the VOLTRA values always the lower value. The agreement between the U-values calculated (for the brick wall and lightweight concrete block wall only) using the procedure specified in BS EN ISO 6946 agreed to with 4% of the measured values. For the ICF walls, there were some significant difference between the lag time of the power that was measured directly with the values obtained using a 0.25 m x 0.25 m HFM and with those calculated using VOLTRA. These differences could not be explained but are discussed.

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Approved on behalf of NPLML by Dr M Cain,
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1 BACKGROUND

Producing low energy consumption buildings is now one of the UK's most urgent objectives. The Government has stated that it will revise the building regulations to ensure we only build zero carbon homes by 2016. The search is on for construction methods that improve the thermal performance of structures without simply adding layers of insulation. One such method is the use of high thermal mass structures. Currently, however, the only way of determining the thermal performance of structures in non-steady conditions is by complex calculations for which there have been little or no attempts to validate by measurement. This situation has been acceptable because only a few, specialised modern structures have attempted to utilise different combinations of thermal mass and insulation to gain thermal advantage. The calculation methods that were adequate for whole building energy calculations are not sufficiently accurate for product and design selection purposes. There is now a need to establish a measurement facility to enable dynamic thermal properties to be directly measured. This facility would then be used to both characterise specific designs and to validate various calculation methodologies.

The measurement challenge is therefore to develop measurement facility and procedures that would enable the thermal performance benefit of using high thermal mass structures to be validated to be able to validate their use in energy efficient buildings.

This project brings together a number of organisations with an interest in developing such measurement methodologies. The National Physical Laboratory the UK's National Measurement Institute carried out the measurements and Glasgow Caledonian University with experience of carrying out thermal performance calculations for the construction industry carried out the dynamic modelling. The group also included seven manufacturers of various types who not only supplied some of the walls for testing but also detailed knowledge of their aspect of the construction industry. This project was 50% funded by the NMS Measurement for Innovators programme. The full list of the partners is given in Table 1.

2 THE PROJECT PARTNERS

The partners are listed in Table 1.

Table 1 List of participating organisations

Company	Main activity
Aggregate Industries Limited	Concrete materials producer and supplier
BASF - The Chemical Company	Manufacturer of additives used in concrete
Glasgow Caledonian University	Experts in calculating thermal performance of building structures
Aircrete Producers Association (APA)	Trade Association for manufacturer of aircrete building blocks
Insulating Concrete Formwork Association (ICFA)	Trade Association for manufacturers of Insulated Concrete Formwork walls
Kier Engineering Services	Construction company and house builder
PolySteel UK Ltd	Manufacturer of Insulated Concrete Formwork walls
Pudlo David Ball Group	Specialist concrete wall installer
The Concrete Centre	Trade Association for the whole concrete industry
National Physical Laboratory	UK's National Measurement Institute.

3 OVERVIEW OF PROJECT OBJECTIVES

i) Adapt the NPL Wall Guarded Hot Box to enable it to carry out thermal performance measurements of structures with the warm side of the structure kept constant and the cold side of the structure cycled over a 24-hour period, though a specific temperature range. The cold side temperature to always be lower than the warm side temperature. Such an arrangement ensures that there would always be heat transfer from the warm chamber of the hot box to the cold chamber and so the warm chamber power could be used to derive the thermal performance of the structure. This was possible because of the nature of the NPL Wall Guarded Hot Box design ensured that the cycling cold chamber temperature did not result in additional heat transfer through the hot chamber walls. A schematic sketch of the Wall Guarded Hot Box is shown in Figure 1.

ii) Build eight walls (only seven were actually built and measured) covering a wide range of wall types found in residential properties. The walls to be built carefully to the documented designs to facilitate subsequent modelling. The details of the walls built and the thermal performance parameters measured and calculated are given in Sections 4 & 5. All the wall panels were 1.2 m x 1.2 m.

iii) Each wall to be instrumented with thermocouples fixed to every interface between different materials (and in the case of the ICF walls one to be also installed in the centre of the concrete), so enabling the temperature profiles through the structures to be recorded whilst the temperature of the cold chamber was being cycled.

iv) For each wall type the following hot box measurements to be carried out:

- A steady state U-value hot box measurement with the temperature of the warm chamber air at 24.5 °C and the cold chamber air temperature at approximately 3 °C

- A dynamic measurement with the temperature of the warm chamber air kept constant at 24.5 °C and the cold chamber air temperature cycled between 3 °C and 15 °C and back to 3 °C over a 24 hour period. This cycling measurement to be carried out twice.

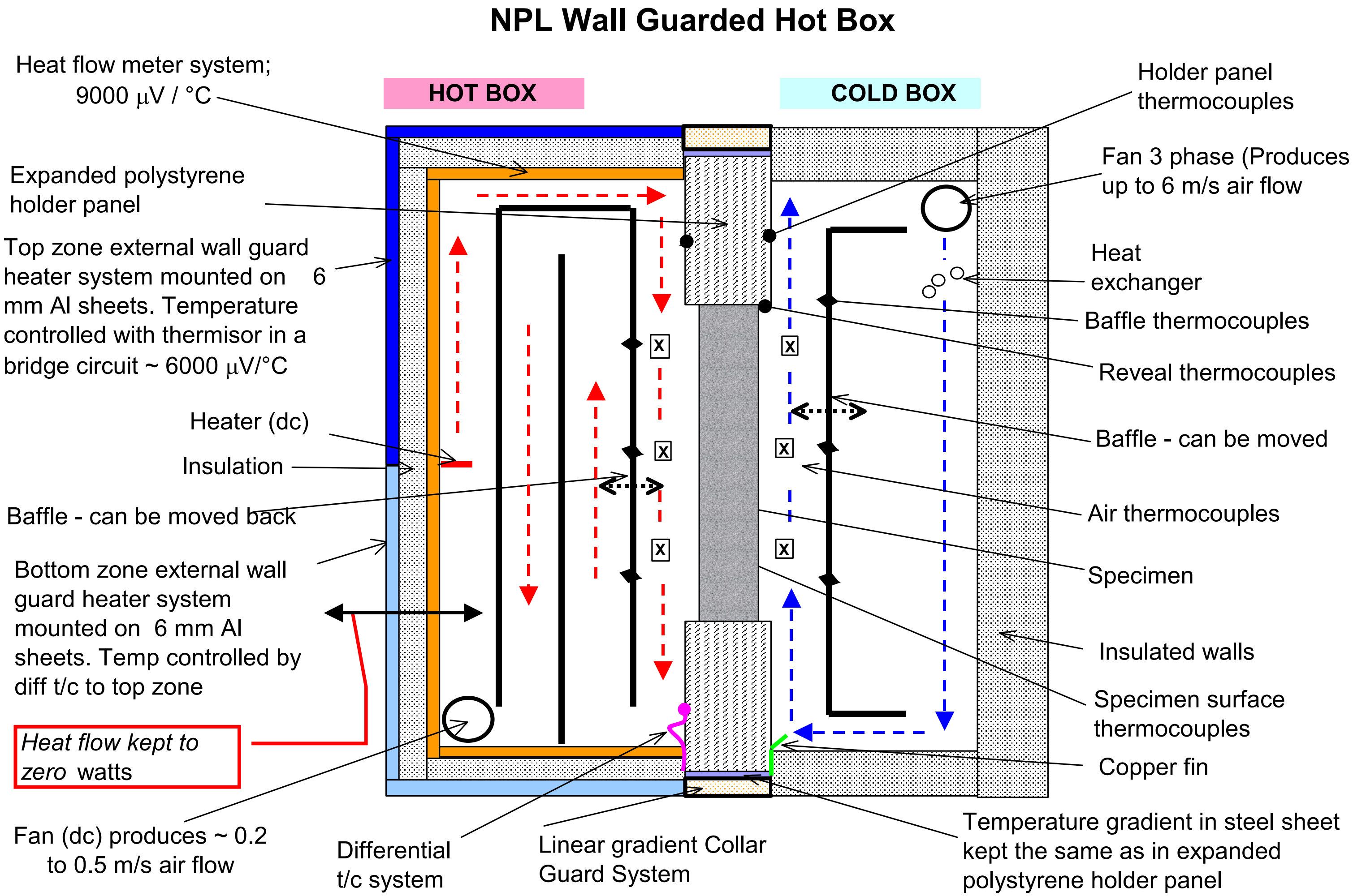
  - Firstly, deriving the power transferred through the wall panel from the measured power into the hot chamber, corrected for power transfer through the expanded polystyrene surround.

  - Secondly, deriving the power transferred through the wall panel from the output of a 0.25 m x 0.25 m heat flux meter (HFM) and the associated guard plates fixed to the centre of the wall.

v) From these steady-state and dynamic hot box measurements, the following performance indicators were to be derived.

a) U-value (W/m^2.K)

Figure 1 Schematic diagram of the Wall Guarded Hot Box



b) Energy (Wh) required to maintain the temperature of the warm chamber air temperature at 24 °C over one complete cycle.

c) The relationship between the measured U-value and the energy used to maintain constant temperature in the warm chamber.

d) Time lag between the maximum temperature difference between the cold chamber and warm chamber and the resulting maximum power transfered through the wall.

e) Time lag between the minimum temperature reached in the cold chamber and the minimum temperature reached on the warm side of the test element.

f) Amplitude of the variation in power transfer through the test element caused by the temperature cycling of the cold chamber.

g) Amplitude of the variation in power transfer through the test element caused by the temperature cycling of the cold chamber as a percentage of the power transferred through the test element in the steady-state.

h) The rolling average of the U-values calculated from the one hourly data sets recorded during the temperature cycling.

i) The difference between the rolling average U-value and the steady state U-value.

vi) The thermal properties of the walls that are measured shall also be modelled by Glasgow Caledonian University, where possible.

4 EXPERIMENTAL DETAILS

4.1 DETAILS OF THE HOT BOX APPARATUS AND THE HFM SENSOR.

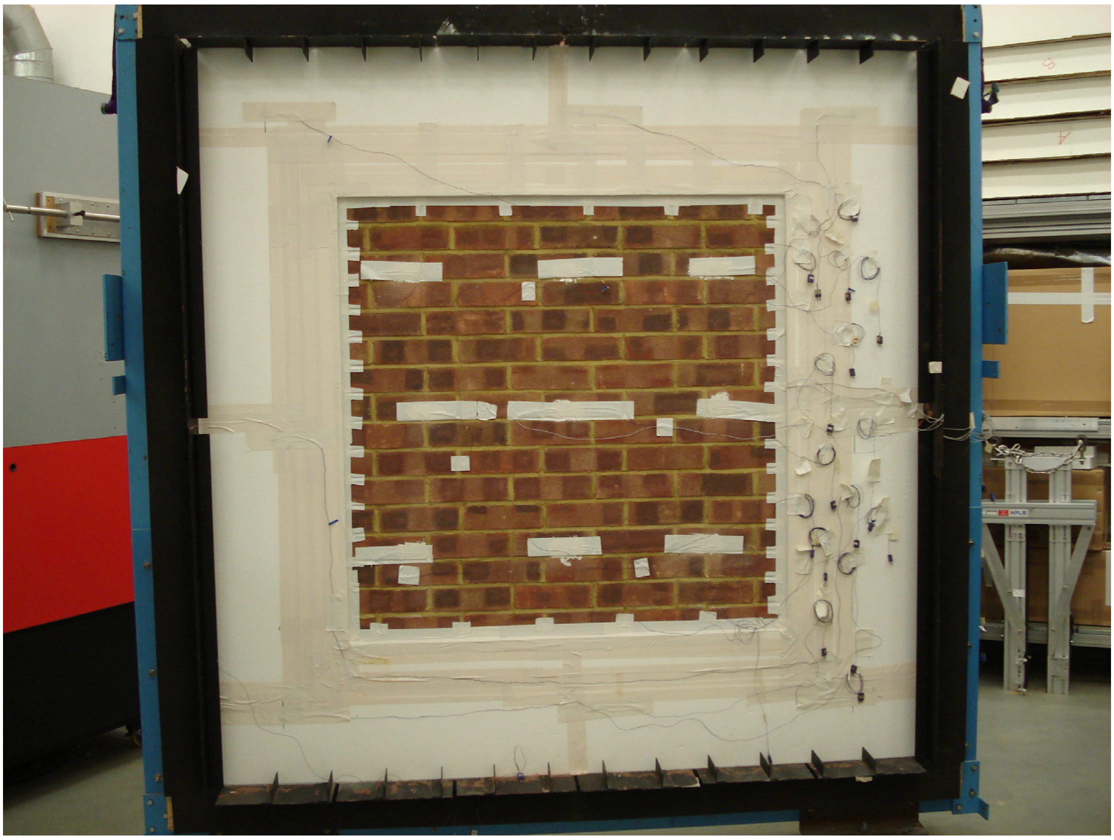
All the measurements were carried out in the NPL Wall Guarded Hot Box Apparatus that conforms to the requirements of BS EN ISO 8990 and is accredited by UKAS to carry out these types of measurement. A schematic diagram of this apparatus is shown in Figure 1 and a photograph of a brick faced wall mounted in the surround panel is shown in Figure 2.

The 1.2 m x 1.2 m wall panels were all measured mounted in a 350 mm thick expanded polystyrene (EPS) surround panel as shown in Figure 2. The aperture of the hot chamber is 2 m x 2 m. To enable the power through the surround panel to be correctly accounted for during the cycling measurements a series of steady-state and cycling measurements were carried out with the surround panel aperture filled with EPS of the same density as the material used in the surround panel.

To carry out steady state U-value measurements the temperature of the warm and cold chambers are established to produce a set temperature difference across the test element (usually 20 °C) and after thermal equilibrium has been reached (when both the power into the warm chamber and the temperatures of the warm and cold chambers are constant) all the temperature and power values are recorded from which the u-value is calculated. To be able to carry out dynamic measurements it was necessary to cycle the temperature of the cold chamber. The cold chamber temperature is controlled by pumping conditioned water/ethylene glycol mixture around a heat exchanger in the cold chamber over which the air is circulate using fans. The temperature of that fluid is controlled by equipment comprising a compressor, heater and pump. To enable the temperature of that fluid to be cycled the temperature controller used to establish the required fluid temperature was changed for a Eurotherm 3058 that has the capability for the set point to be programmed in a variety of ways. This controller was programmed to vary the set point over the range 3 °C to 15 °C and back to 3 °C over a 24 hour period, as a sinusoidal function.

All of the cycling measurements were duplicated using a commercial heat flow meter (HFM) to measure the power through each wall instead of the corrected warm chamber power. This 0.25 m x 0.25 m HFM was recalibrated for the purposes of this project in the NPL 610 mm Guarded Hot Plate apparatus. When the HFM was attached to the warm face of each wall it was surrounded by guard plates made of the same material as the HFM. In these measurements it was the thermal conductance of the walls that was measured not the thermal transmittance.

Figure 2 Photograph of a wall in the surround panel of the WGHB



4.2 DETAILS OF THE CALCULATION AND MODELLING METHODS

The steady state U-values were calculated using the following methods:

- Physibel VOLTRA (by Glasgow Caledonian University).
- EN 6946 (by NPL)

The dynamic thermal performance of the structures were calculated using Physibel VOLTRA by Glasgow Caledonian University. The modelling is described in more detail in Section 7.

4.3 DETAILS OF THE WALLS.

A summary of the wall structures used in this project is shown in Table 2

Table 2 Summary of wall construction details

Wall no.	Description	Plasterboard fixing details
WALL 1	**ICF -** 9 mm ceramic floor tiles instead of acrylic render / 65 mm 24 kg/m^3 EPS on both sides & 150 mm thick 2400 kg/m^3 concrete / plaster board (for details see comments) & STEEL connectors - **(BUILT BY POLYSTEEL)**	Fixed on 10 mm thick wood blocks imitating dob & dab
WALL 2	Timber frame - 15 mm thick tongue & groove wood cladding. Wood studs (11% wood) 44 mm thick & 140 mm deep. Knauf Timber Slab glass fibre insulation between the studs **- BUILT BY NPL**	Plaster board fixed in it's only natural position
WALL 3	NPL Standard wall - 102 mm Brick / 45 mm air cavity / 55 mm Celotex / 100 mm AAC / 10 mm air cavity / 12 mm plasterboard (for details of fixing see comments) - 3 stainless steel wall ties **- BUILT BY NPL**	Fixed on 10 mm thick wood blocks imitating dob & dab AND without the plasterboard
WALL 4	ICF - 9 mm ceramic floor tiles instead of acrylic render / 65 mm NEOPOR Insulation on both sides & 150 mm thick 2400 kg/m^3 concrete / plaster board (for details of fixing see comments) & Steel connectors - **(BUILT BY POLYSTEEL)**	Fixed on 10 mm thick wood blocks imitating dob & dab
WALL 5	**Not built**	
WALL 6	ICF - 9 mm ceramic floor tiles instead of acrylic render / 65 mm 24 kg/m^3 EPS on both sides & 150 mm thick 2400 kg/m3 concrete / plaster board (for details of fixing see comments) & PLASTIC connectors **(BUILT BY POLYSTEEL)**	Fixed on 10 mm thick wood blocks imitating dob & dab *There is already a high thermal resistance on the warm side (the 65 mm EPS) - the additional 10 mm air gap should not have a significant effect on the dynamic thermal properties.*
WALL 7	APA wall - 9 mm ceramic floor tiles instead of acrylic render / 80 mm Celatex insulation / 200 mm thick AAC block / air cavity / plasterboard (for details of fixing see comments) **(BUILT BY APA IN NPL HOT BOX)**	Fixed on 10 mm thick wood blocks imitating dob & dab ONLY
WALL 8	Concrete Centre - Brick/cavity/55 mm Celotex /lightweight agregate concrete/ air cavity / plasterboard (for details of fixing see comments) - 3 stainless steel wall ties **BUILT BY NPL**	Fixed on 10 mm thick wood blocks imitating dob & dab and NO plasterboard
WALL 9	Aperture in EPS surround panel filled in with 350 mm thick EPS to make a solid EPS test element.	A series of steady state and dynamic measurements were made on this wall to remove the heat flux component associated with the EPS surround panel.

A sketch of each wall type is given in Figures 3 to 9

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Figure 3 Drawing of Wall 1 - ICF Wall with EPS and steel connectors

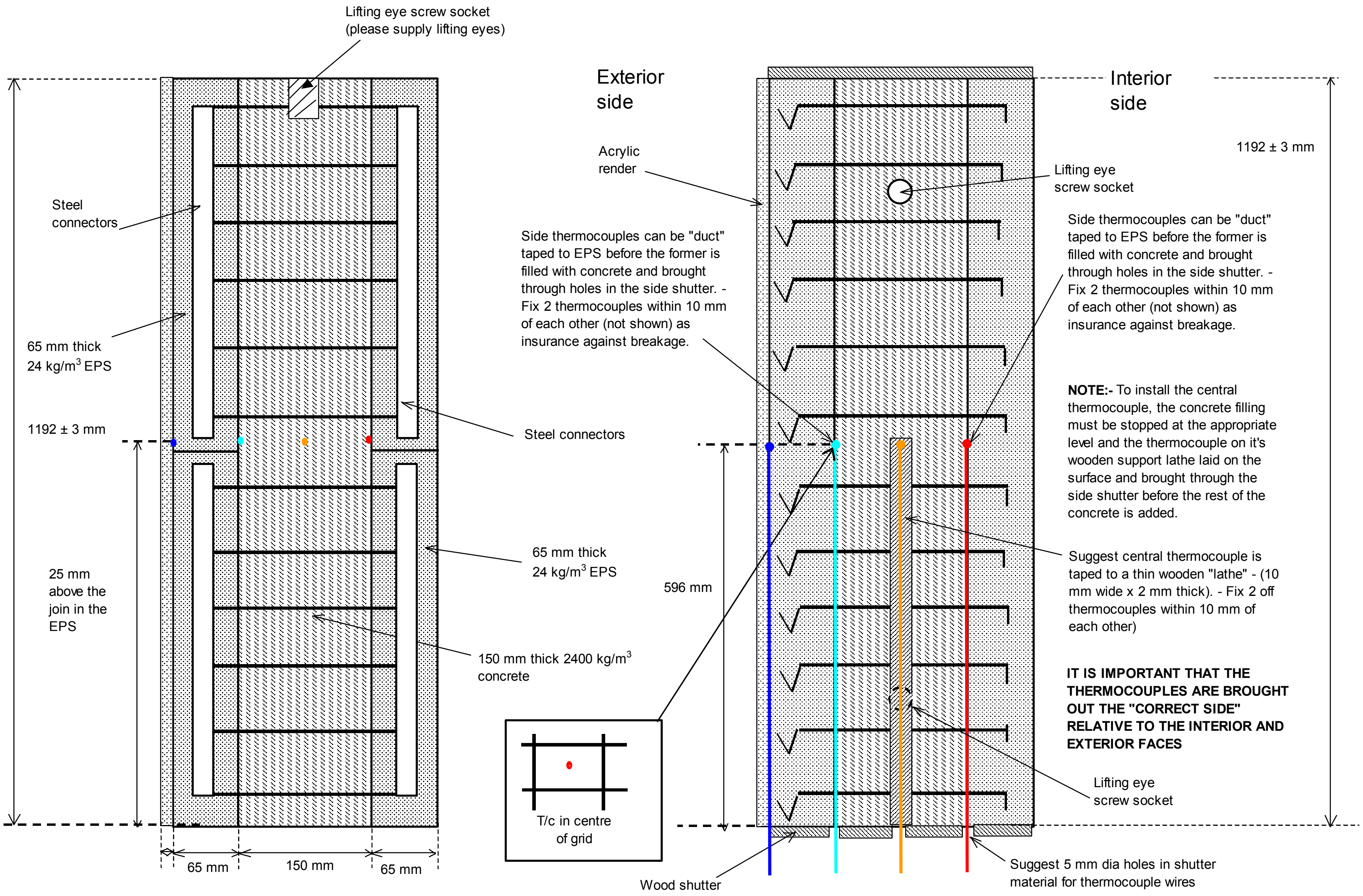


Figure 4 Drawing of Wall 2 - Timber frame wall

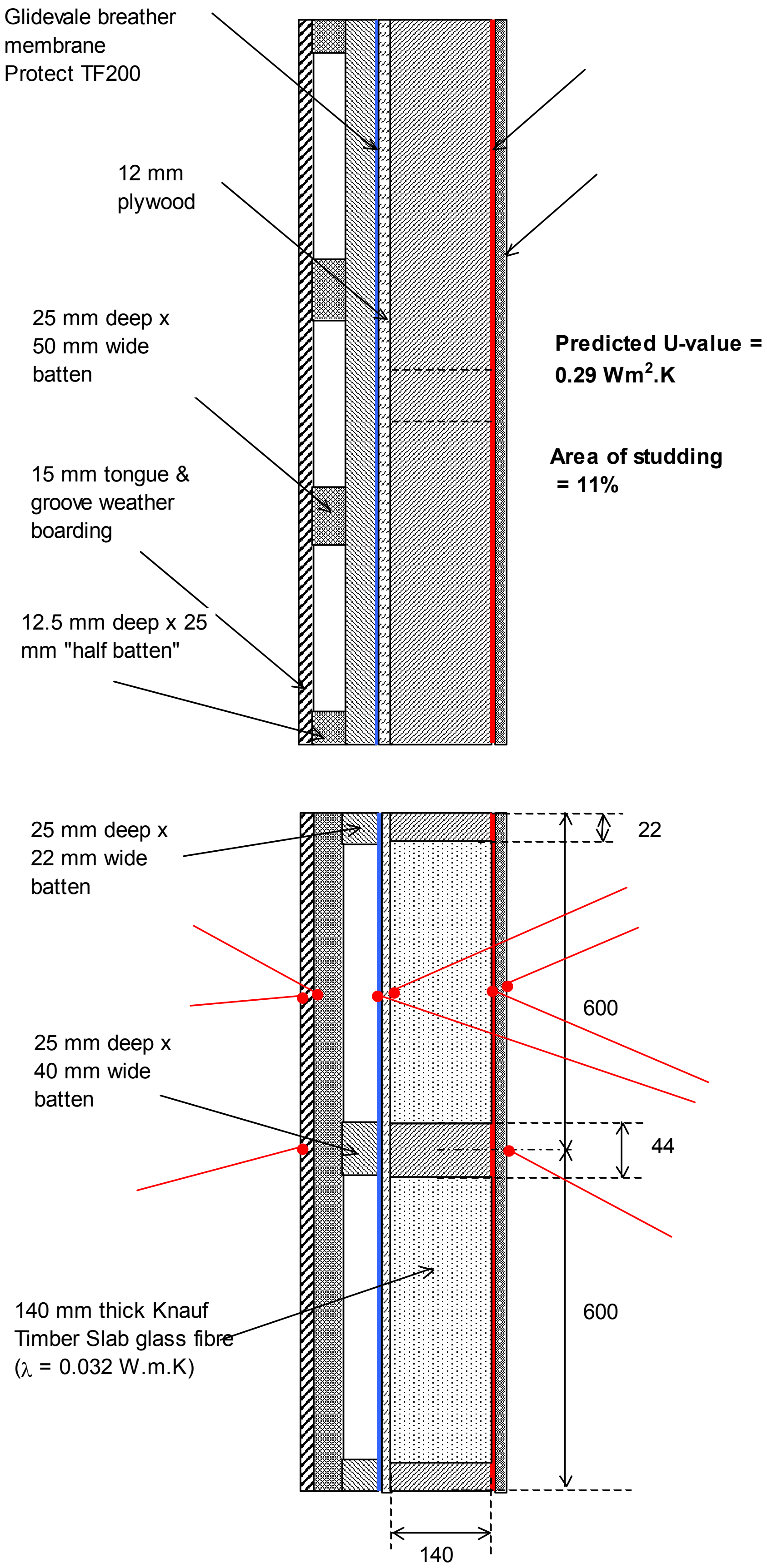


Figure 5 Drawing of Wall 3 – Brick/PUR/AAC

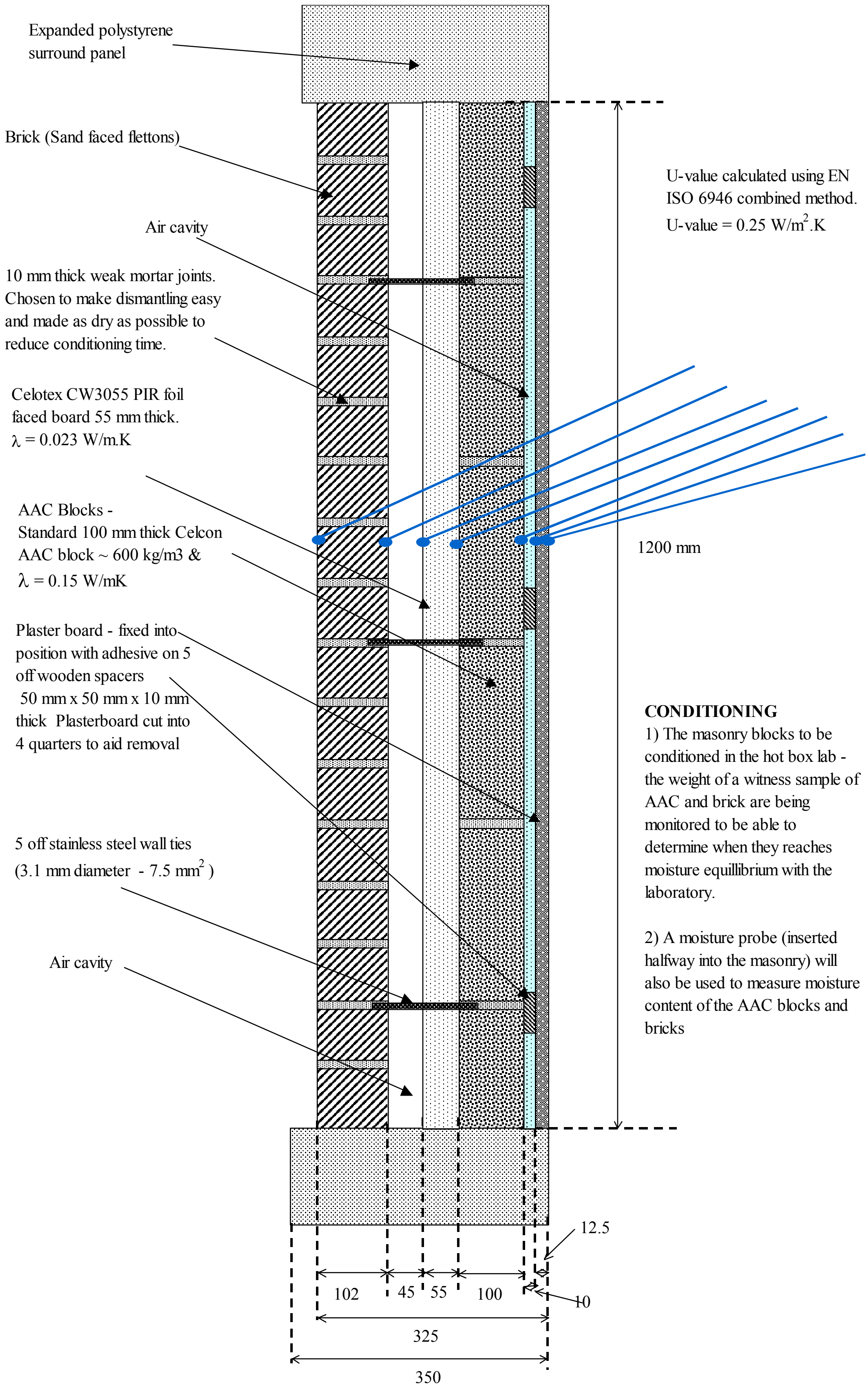


Figure 6 Drawing of Wall 4 - ICF wall with Neopor and steel connectors

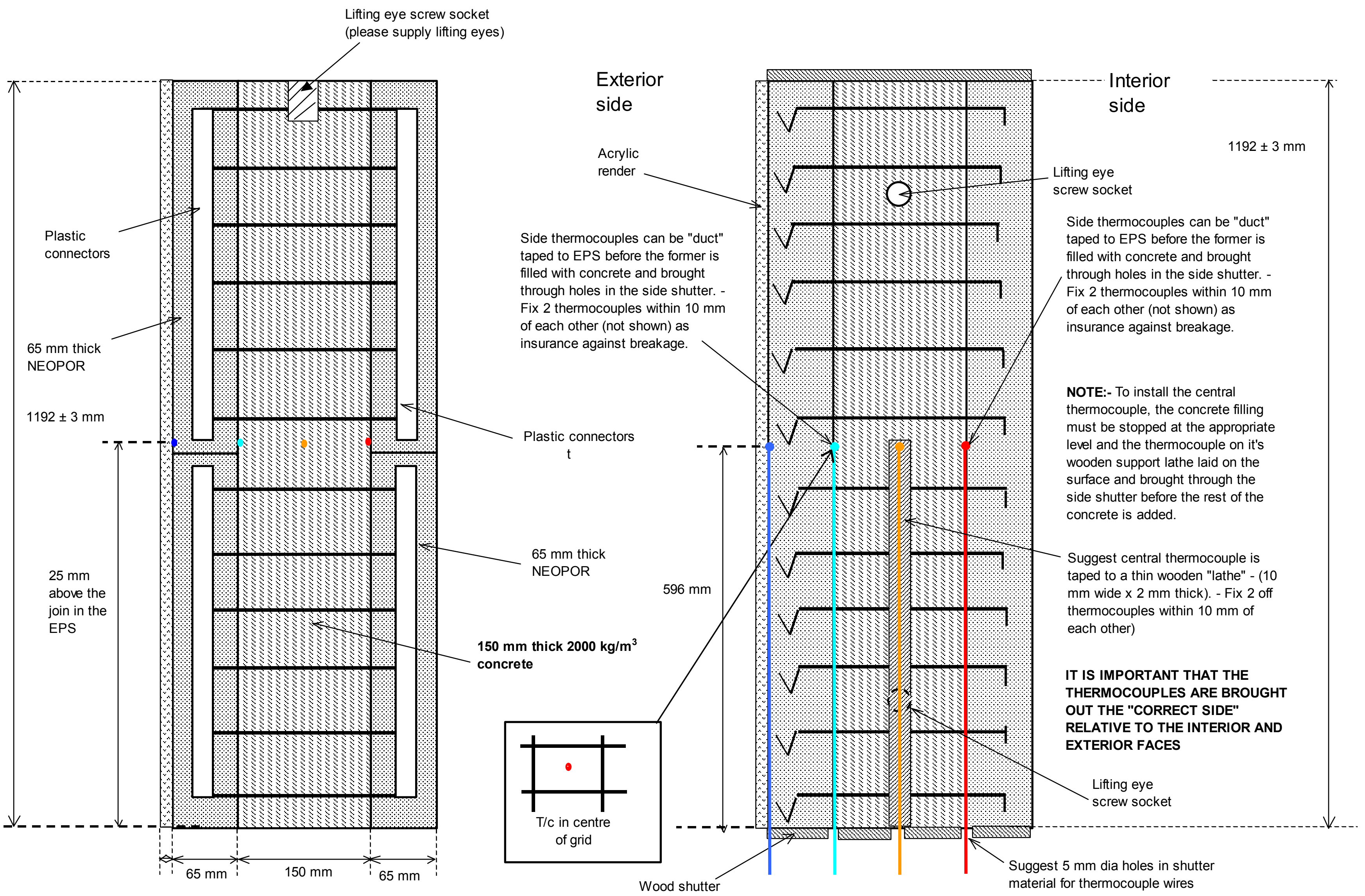


Figure 7 Wall 6 - ICF Wall with EPS and plastic connectors

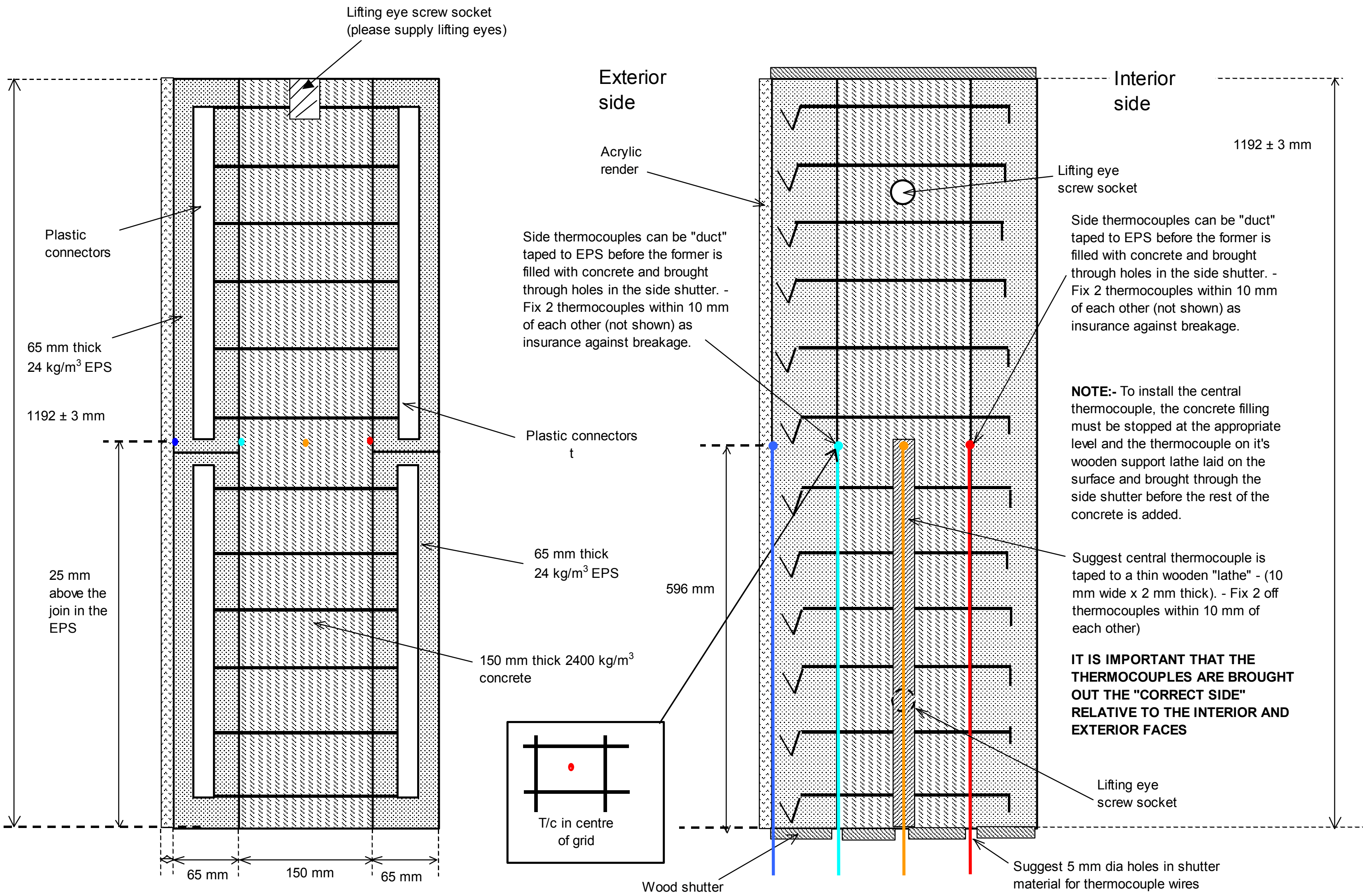


Figure 8 Drawing of Wall 7 - AAC Wall

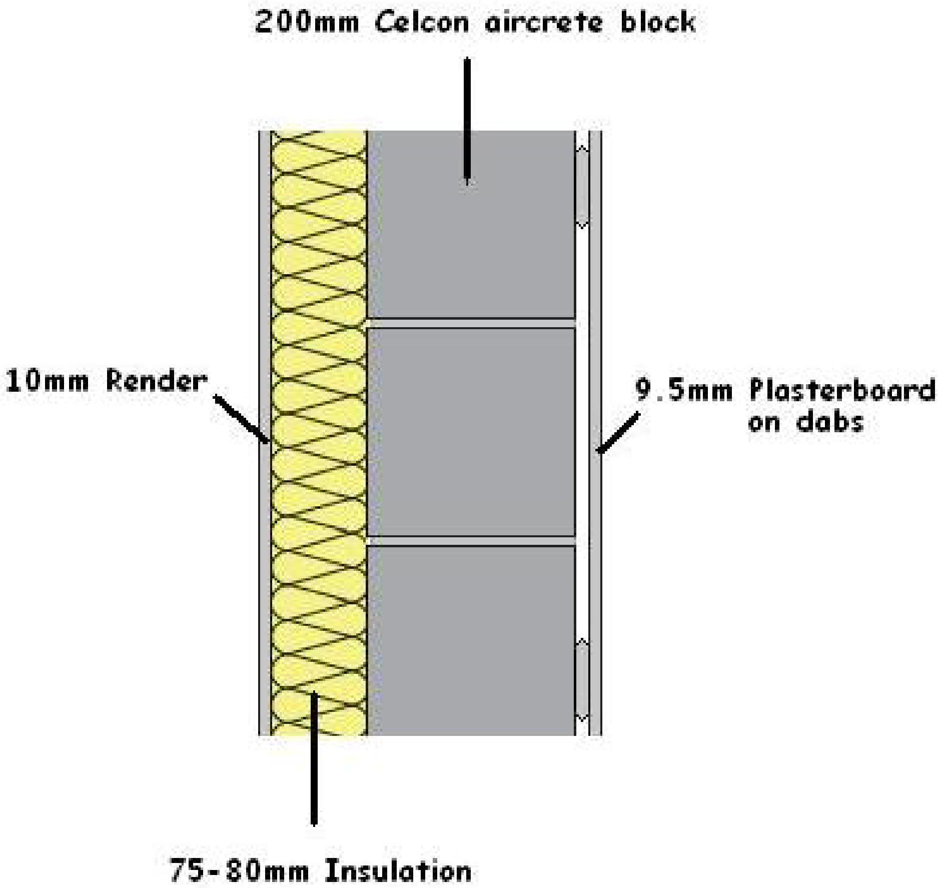
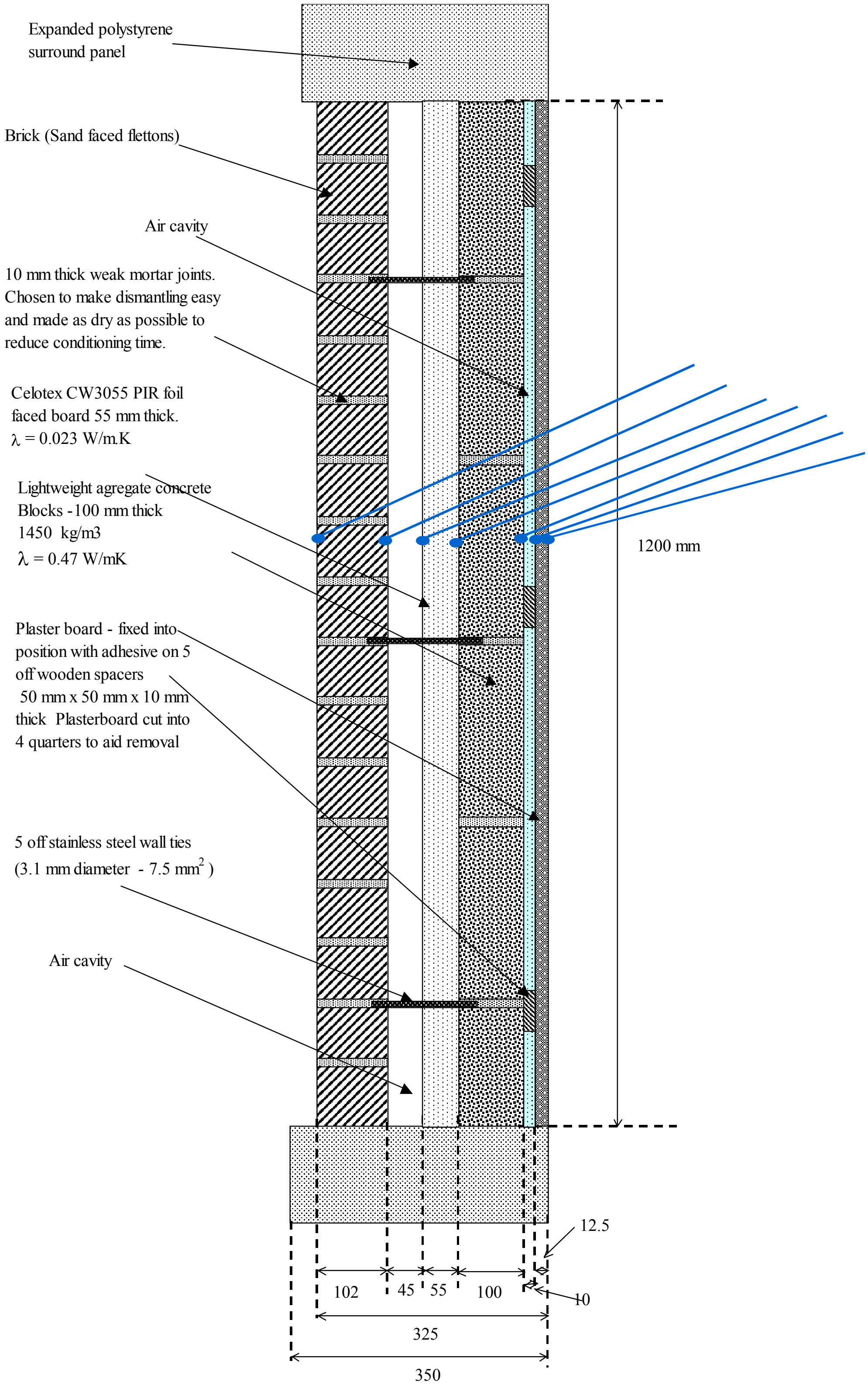


Figure 9 Drawing of Wall 8 - Concrete block wall



The details of the various components of the seven walls and the thermophysical property data used to carry out the various calculations are given in Tables 3 to 9.

Table 3 Specification of the components of Wall 1

Wall 1	ICF wall	Built by Polysteel		TT369
Predicted U-value		**0.3**	W/m^2.K	
Overall thickness		**310**	mm	Assumes a 10mm gap between EPS & Plasterboard
ACRYLIC Render	thickness	9	mm	Ceramic floor tile used to simulate Acrylic render
	thermal conductivity	0.85	W/m.K	CIBSE Guide A - 3-38
	density	1900	kg/m^3	CIBSE Guide A - 3-38
	Specific heat	850	J.kg^{-1}.K^{-1}	CIBSE Guide A - 3-38
EPS	thickness	65	mm	
both sides	density	24	kg/m^3	
	thermal conductivity	0.033	W/m.K	
	Specific heat	1450	J.kg^{-1}.K^{-1}	
Concrete	thickness	150	mm	150mm C25/30 standard pour able mix concrete (150mm slump, 10mm rounded aggregate) 2400 kg/m^3
	density	2400	kg/m^3	
	specific heat	1000	J.kg^{-1}.K^{-1}	"Protected" value from CIBSE Guide A
	thermal conductivity	1.75	W/m.K	"Protected" value from CIBSE Guide A
Plasterboard	thickness	12.5	mm	Glued on wood blocks 10 mm thick to avoid wet paster
	density	700	kg/m^3	
	thermal conductivity	0.21	W/m.K	CIBSE Guide A
	specific heat	1000	J.kg^{-1}.K^{-1}	
Bonding ties	Material	Steel		**Steel**
	diameter			See figure 10
	number per m^2			
	description of installation			
Thermocouple positions	On EPS between EPS and render			**Position of thermocouples (t/cs) in each plane**
	On concrete between the concrete and the EPS (Cold side)			* All t/cs to be in the same position through the stack
	In the centre of the concrete			* exactly central in the 1.2 m x 1.2 m face
	On concrete between the concrete and the EPS (warm side			
	On EPS between EPS and air cavity behond plasterboard			
	On plasterboard between plaster board and air cavity behind it			
Special features	Two eye bolt sockets caste into the top surface of the concrete to enable the unit to be lifted by crane			

Figure 10 Sketch of steel connectors used in ICF walls

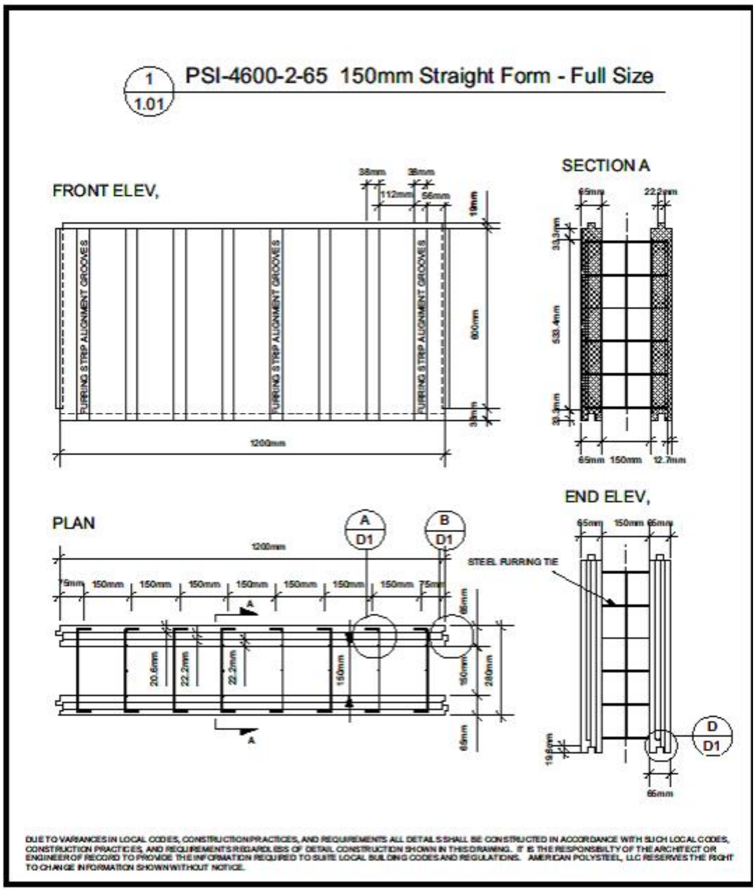


Table 4 Specification of the components of Wall 2

Wall 2	**Timber wall**	**Built by NPL**		**TT366**
Predicted U-value		**0.27**	W/m^2.K	
Overall thickness		**308**	mm	
Wood tongue & groove cladding	thickness	14.6	mm	
	density	500	kg/m^3	CIBSE Guide A Table 3.47
	thermal conductivity	0.13	W/m.K	
	specific heat	1600	J.kg^{-1}.K^{-1}	
Air cavity	thickness	45	mm	
(unvented)	thermal resistance	0.46	m^2.K/W	BS EN ISO 6946 ($\Delta\theta < 5$ K) The emissivity of the aluminium cladding of the Celotex is assumed to be 0.2
Breather membrane	type	Glidevale		Glidevale breather membrane - Protect TF200
Plywood	thickness	9	mm	
	density	540	W/m.K	
	thermal conductivity	0.12	kg/m^3	CIBSE Table 3.39
	Specific heat	1210	J.kg^{-1}.K^{-1}	
Stud	Material	wood		11%
	width	44	mm	Only the centre stud the outside studs were 22 mm wide
	depth	140	mm	
	distance between centres	600	mm	
	density	510	W/m.K	
	thermal conductivity	0.12	kg/m^3	CIBSE Table 3.39
	specific heat	1380	J.kg^{-1}.K^{-1}	
Insulation	Material	Glass fibre		140 mm deep Knauf Dritherm Cavity Slab 32
	thickness	140	mm	
	density	n/a		
	Thermal conductivity	0.032	W/m.K	
	specific heat	1030	J.kg^{-1}.K^{-1}	
Vapour control barrier	Type	?		TP Polythene DPM - 250 MU PIFA BLUE
Plasterboard	thickness	12.5	mm	Not Al backed - mounted on wooden blocks to imitate plaster
	density	700	kg/m^3	dabs - keeping plasterboard 12 mm from membrane.
	thermal conductivity	0.21	W/m.K	**CIBSE Guide A**
	Specific heat	1000	J.kg^{-1}.K^{-1}	
Thermocouple positions	On inside brick leaf surface			Position of thermocouples (t/cs) in each plane
	On Membrane			* All t/cs to be in the same position through the stack
	On warm side of OSB cladding			* exactly central in the 1.2 m x 1.2 m face
	On inside of plasterboard			

Table 5 Specification of the components in Wall 3

Wall 3	**Standard brick/insulation/AAC wall**			**TT363**
Predicted U-value		**0.25**	W/m^2.K	
Measured U-value		**0.27**	W/m^2.K	
Overall thickness		**325**	mm	
Render	None			
Brick	Type			Sand faced flettons
	thickness	102	mm	
	density	1750	kg/m^3	
	thermal conductivity	0.77	W/m.K	CIBSE Guide A
	Specific heat	1000	J.kg^{-1}.K^{-1}	
Insulation	Material	PIR		Celotex CW3055 Foil faced board
	thickness	55	mm	
	density	30	kg/m^3	Manufacturers data
	Thermal conductivity	0.023	W/m.K	Manufacturers data
	Specific heat	1400	J.kg^{-1}.K^{-1}	CIBSE Guide A - Table 3.47
Air cavity	thickness	45	mm	
(unvented)	thermal resistance	0.46	m^2.K/W	BS EN ISO 6946 ($\Delta\theta < 5$ K) The emissivity of the aluminium cladding of the Celotex is assumed to be 0.2
AAC blocks	type			H H Celcon
	thickness	100	mm	Manufacturers data
	density	600	kg/m^3	Manufacturers data
	Thermal conductivity	0.15	W/m.K	Manufacturers data
	Specific heat	1000	J.kg^{-1}.K^{-1}	CIBSE Guide A - Table 3.47
Plasterboard	thickness	12.5	mm	Glued on wood blocks 10 mm thick to avoid wet paster
	density	700	kg/m^3	
	thermal conductivity	0.21	W/m.K	Data taken from CIBSE Guide A
	Specific heat	1000	J.kg^{-1}.K^{-1}	Data taken from CIBSE Guide A
Thermocouple positions	On inside brickwork			**Position of thermocouples (t/cs) in each plane**
	on Celotex surface facing air cavity			* All t/cs to be in the same position through the stack
	On Celotex surface facing AAC			* exactly central in the 1.2 m x 1.2 m face
	On warm side of AAC			
	On inside plasterboard			

Table 6 Specification of the components of Wall 4

Wall 4	ICF wall	Supplied by PolySteel		TT371
Predicted U-value		0.28	W/m^2.K	
Overall thickness		310	mm	
Acrylic render	thickness	9	mm	Ceramic floor tile - to simulate Acrylic render
	thermal conductivity	0.85	W/m.K	CIBSE Guide A - 3-36
	density	1900	kg/m^3	CIBSE Guide A - 3-36
	specific heat		J.kg^{-1}.K^{-1}	
Neopor	thickness	65	mm	Manufacturer's data
	density	24	kg/m^3	
	thermal conductivity	0.03	W/m.K	
	specific heat	1210	J.kg^{-1}.K^{-1}	
Concrete	thickness	150	mm	150mm C25/30 standard pour able mix concrete (150mm slump, 10mm rounded aggregate)
	density	2400	kg/m^3	
	Specific heat	1000	J.kg^{-1}.K^{-1}	"Protected" value from CIBSE Guide A
	thermal conductivity	1.75	W/m.K	"Protected" value from CIBSE Guide A
Neopor	thickness	65	mm	Neopor
	density	24	kg/m^3	
	thermal conductivity	0.03	W/m.K	
	specific heat	1210	J.kg^{-1}.K^{-1}	
Plasterboard	thickness	12.5	mm	Glued on wood blocks 10 mm thick to avoid wet paster
	density	700	kg/m^3	
	thermal conductivity	0.21	W/m.K	Data taken from CIBSE Guide A
	Specific heat	1000	J.kg^{-1}.K^{-1}	Data taken from CIBSE Guide A
Bonding ties	Material	Steel		Drawing shown in figure 10
	diameter	?		
	number per m^2	?		
Thermocouple positions	On EPS between EPS and render			**Position of thermocouples (t/cs) in each plane**
	On concrete between the concrete and the EPS (Cold side)			* All t/cs to be in the same position through the stack
	In the centre of the concrete			* exactly central in the 1.2 m x 1.2 m face
	On concrete between the concrete and the EPS (warm side			
	On EPS between EPS and air cavity behond plasterboard			
	On plasterboard between plaster board and air cavity behind it			
Special features	Two eye bolt sockets caste into the top surface of the concrete to enable the units to be lifted by crane			

Table 7 Specification of the components of Wall 6

Wall 6	ICF wall - Built by Polysteel			TT370
Predicted U-value		**0.22**	W/m^2.K	
Overall thickness		**311**	mm	301 mm if Plasterboard glued direct to concrete
Acrylic render	thickness	9	mm	Ceramic floor tile - to simulate Acrylic render
	thermal conductivity	0.85	W/m.K	CIBSE Guide A - 3-36
	density	1900	kg/m^3	CIBSE Guide A - 3-36
	Specific heat	850	J.kg^{-1}.K^{-1}	CIBSE Guide A - 3-38
EPS	thickness	65	mm	Manufacturer's data
	density	24	kg/m^3	
	thermal conductivity	0.033	W/m.K	
	Specific heat	1450	J.kg^{-1}.K^{-1}	
Concrete	thickness	150	mm	150mm C25/30 standard pour able mix concrete (150mm
	density	2400	W/m.K	slump, 10mm rounded aggregate) 2400 kg/m3
	thermal conductivity	1.7	kg/m^3	CIBSE Guide A value
EPS	thickness	65	mm	Manufacturer's data
	density	24	kg/m^3	
	thermal conductivity	0.033	W/m.K	
	Specific heat	1450	J.kg^{-1}.K^{-1}	
Plasterboard	thickness	12.5	mm	Glued on wood blocks 10 mm thick to avoid wet paster
	density	700	kg/m^3	
	thermal conductivity	0.21	W/m.K	Data taken from CIBSE Guide A
	Specific heat	1000	J.kg^{-1}.K^{-1}	Data taken from CIBSE Guide A
Bonding ties	Material	Plastic		Plastic - for details see figure 11
Thermocouple positions	On EPS between EPS and render			Position of thermocouples (t/cs) in each plane
	On concrete between the concrete and the EPS (Cold side)			* All t/cs to be in the same position through the stack
	In the centre of the concrete			* exactly central in the 1.2 m x 1.2 m face
	On concrete between the concrete and the Plasterboard			
	On EPS between EPS and air cavity behond plasterboard			
	On plasterboard between plaster board and air cavity behind it			
Special features	Two eye bolt sockets caste into the top surface of the concrete to enable the unit to be lifted by crane.			

Figure 11 Plastic connectors used in ICF wall

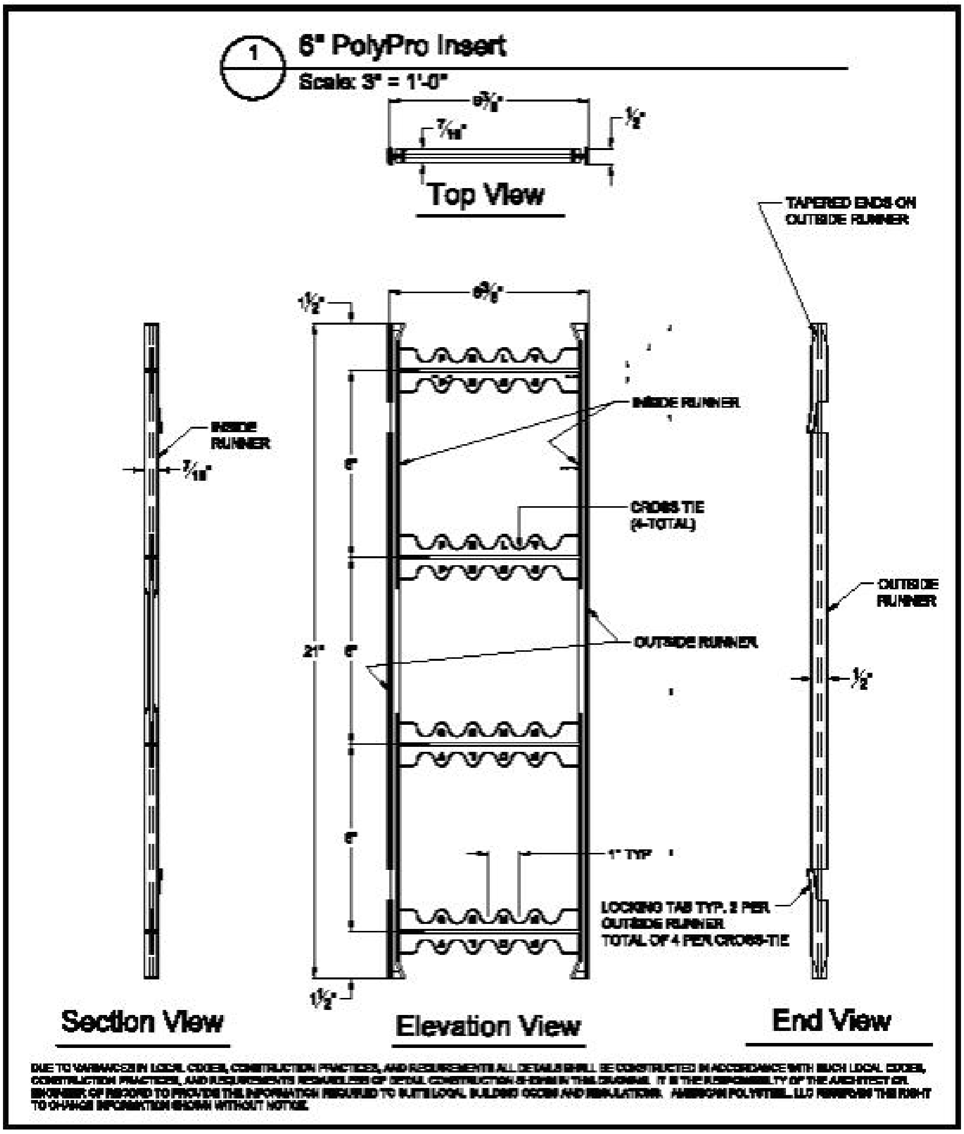


Table 8 Specification of the components of Wall 7

Wall 7	Solid AAC Wall	Supplied by APA		TT368
Predicted U-value		0.22	W/m^2.K	
Overall thickness		305	mm	
Render	thickness	9	mm	Ceramic floor tile - to simulate Acrylic render
	thermal conductivity	0.85	W/m.K	CIBSE Guide A - 3-36
	density	1900	kg/m^3	CIBSE Guide A - 3-36
	Specific heat	850	J.kg^{-1}.K^{-1}	CIBSE Guide A - 3-38
Celatex	thickness	80	mm	This made up of a 55 mm thick & 25 mm thick Celatex insulation glued together (No Nails)
	density	30	kg/m^3	
	thermal conductivity	0.023	W/m.K	
	Specific heat	1400		Manufacturer's data
Celcon Aircrete block	thickness	200	mm	
	density	600	kg/m^3	
	thermal conductivity	0.15	W/m.K	Manufacturer's data
	Specific heat	1000		
Plasterboard	thickness	12.5	mm	Glued on wood blocks 10 mm thick to avoid wet paster
	density	700	kg/m^3	
	thermal conductivity	0.21	W/m.K	Data taken from CIBSE Guide A
	Specific heat	1000	J.kg^{-1}.K^{-1}	Data taken from CIBSE Guide A
Thermocouple positions	On Insulation between Insulation and render			**Position of thermocouples (t/cs) in each plane**
	On AAC between the AAC and the Insulation (Cold side)			* All t/cs to be in the same position through the stack
	On AAC between AAC and air cavity behind plasterboard			* exactly central in the 1.2 m x 1.2 m face
	On plasterboard between plaster board and air cavity behind it			

Table 9 Specification of the components of Wall 8

Wall 8	Standard brick/insulation/lighweight agregate block wall		Built by NPL for The Concrete Centre	TT364
Predicted U-value		0.25	$W/m^2.K$	
Overall thickness		342	mm	
Render	thickness	9	mm	Ceramic floor tile - to simulate Acrylic render
	thermal conductivity	0.85	W/m.K	CIBSE Guide A - 3-38
	density	1900	kg/m^3	CIBSE Guide A - 3-38
	Specific heat	850	$J.kg^{-1}.K^{-1}$	CIBSE Guide A - 3-38
Brick	Type			Sand faced flettons
	thickness	102	mm	
	density	1750	kg/m^3	(approximately) - taken from CIBSE Guide A 2006
	thermal conductivity	0.77	W/m.K	(approximately) - taken from CIBSE Guide A 2006
	Specific heat	1000	$J.kg^{-1}.K^{-1}$	
Insulation	Material	PIR		Celotex CW3055 Foil faced board
	thickness	55	mm	
	density	30	kg/m^3	
	Thermal conductivity	0.023	W/m.K	
	Specific heat	1400	J.kg-1.K-1	
Air cavity	thickness	45	mm	
(unvented)	thermal resistance	0.46	$m^2.K/W$	BS EN ISO 6946 ($\Delta\theta$ < 5 K) The emissivity of the aluminium cladding of the Celotex is assumed to be 0.2
Aggregate block	type			Tarmac Hemelite Standard block or equivalent (7.3 N/mm2)
	thickness	100	mm	
	density	1450	kg/m^3	(7.3 N/mm2 block)
	Thermal conductivity	0.47	W/m.K	(7.3 N/mm2 block) Manufacturer's data
Plasterboard	thickness	12.5	mm	Glued on wood blocks 10 mm thick to avoid wet paster
	density	700	kg/m3	(approximately) - taken from CIBSE Guide A 2006
	thermal conductivity	0.21	W/m.K	(approximately) - taken from CIBSE Guide A 2006
	Specific heat	1000	$J.kg^{-1}.K^{-1}$	
Thermocouple positions	On Insulation between Insulation and render			Position of thermocouples (t/cs) in each plane
	On AAC between the AAC and the Insulation (Cold side)			* All t/cs to be in the same position through the stack
	On AAC between AAC and air cavity behind plasterboard			* exactly central in the 1.2 m x 1.2 m face
	On plasterboard between plaster board and air cavity behind it			

5 DETAILS OF THERMAL PERFORMANCE MEASUREMENTS

5.1 MEASUREMENT AND ANALYSIS DETAILS – STEADY STATE U-VALUES

The steady state U-value of each wall was measured with the temperature of the warm chamber air at 24.5 °C and the cold chamber air temperature at approximately 3 °C

The wall U-values were determined using the Hot Box apparatus. After thermal equilibrium was established the power through the test element was derived from the total power into the warm chamber and the power calculated to have transferred through the surround panel. Then from the recorded average temperatures of the wall surface, baffle and air, in both the warm and cold chambers, the environmental temperature difference was calculated. The U-value was then calculated by dividing the density of heat flow rate through the test element by the environmental temperature difference across it.

For the purposes of this project additional thermocouples (to the normal thermocouples fixed to the outer surfaces) were installed inside all of the walls during their construction. In general a thermocouple was attached at every material interface. In the case of the timber wall further thermocouples were installed to enable the temperature differences between the "homogeneous" part of the wall and in line with the timber studs to be determined.

5.2 MEASUREMENT AND ANALYSIS DETAILS – DYNAMIC MEASUREMENTS

5.2.1 Using the hot chamber power

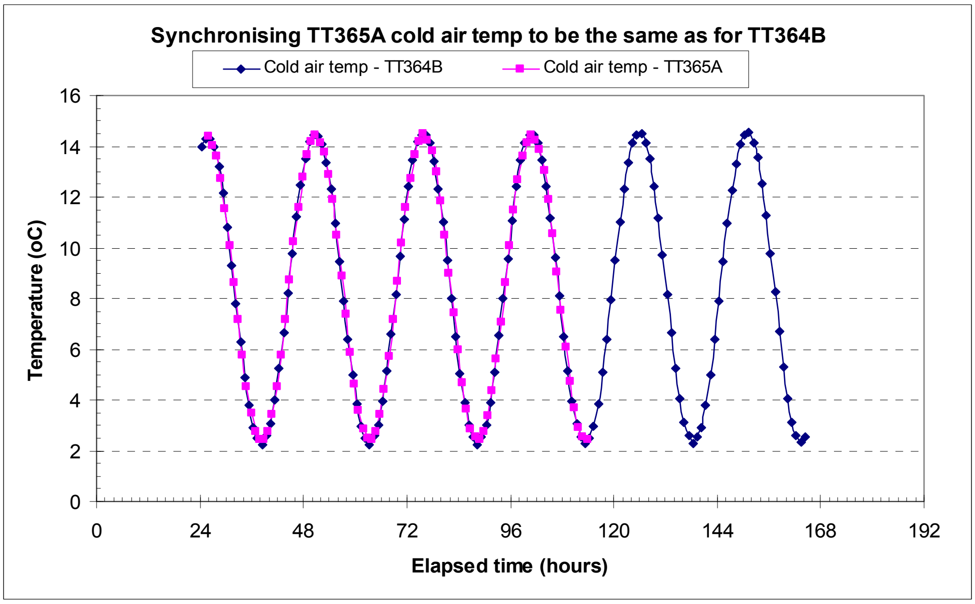
The dynamic thermal performance measurements were made whilst cycling the Hot Box;
's cold chamber temperature. These were achieved by keeping the air temperature in the warm chamber constant at approximately 24.5 °C whilst the air temperature of the cold chamber was cycled between 2.4°C and 14.4 °C over a 25 hour period.

During the cycling measurements the total power supplied to the warm chamber was recorded once every hour. That total power figure has two components i) the power transferred through the surround panel and ii) the power transferred through the wall. Therefore, the power being transferred through the surround panel during these cycling measurements had to be determined and subtracted from the total.

To determine the power transferred through the EPS surround panel for these dynamic measurements, a series of cycling measurements were undertaken with the aperture in the surround panel filled with expanded polystyrene.

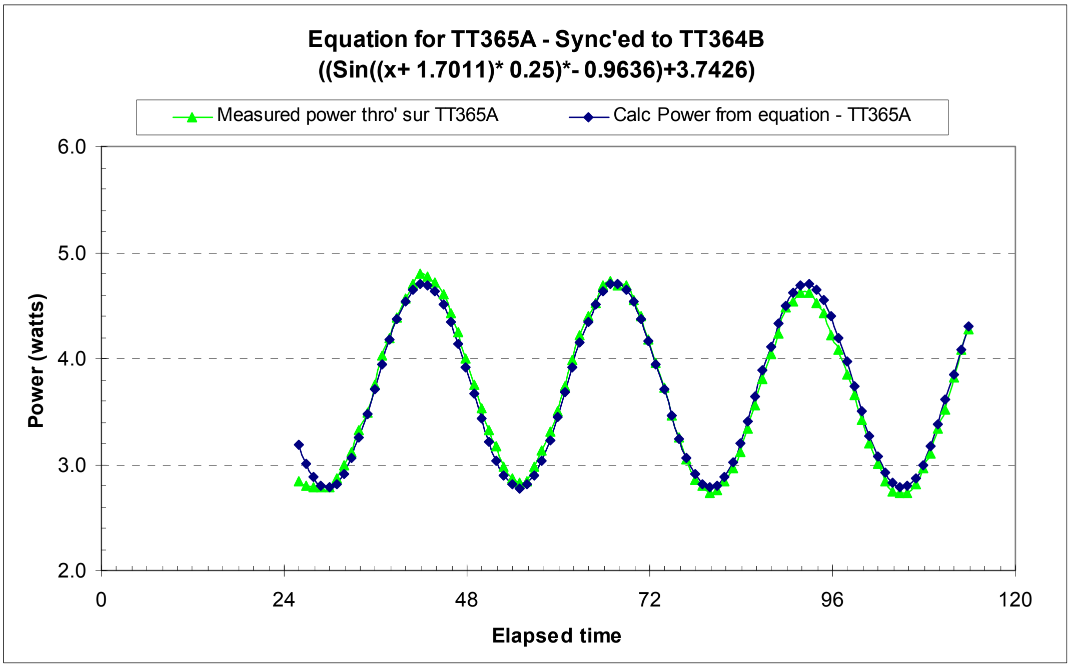
To derive an equation relating time to power transferred through the EPS surround panel that related to a specific measurement of a wall in the surround panel, the time base of the EPS measurements was modified to bring the cold air temperature cycles for the wall plus EPS into phase with the data for the EPS alone (see Figure 12)

Figure 12 Synchronising the time base of the EPS vs cold air temperature graph to match the phase of the Wall + EPS vs cold air temperature graph



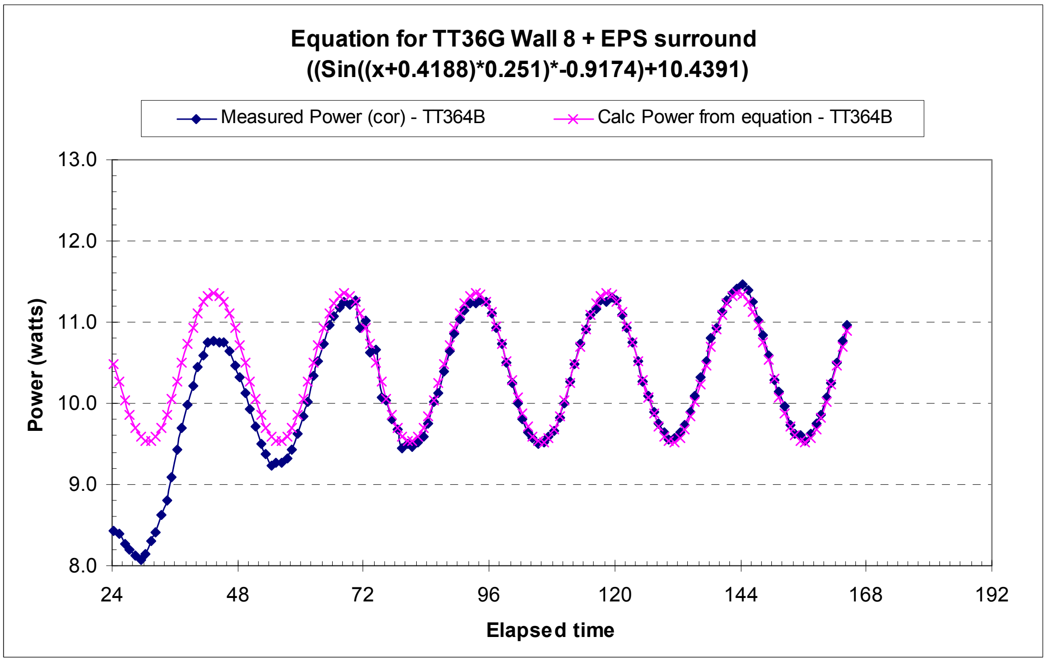
An equation relating the power through the surround panel for a given cold air temperature of this modified data set was then obtained – see Figure 13.

Figure 13 Deriving equation relating cold air temperature and power through the test element for the surround panel.



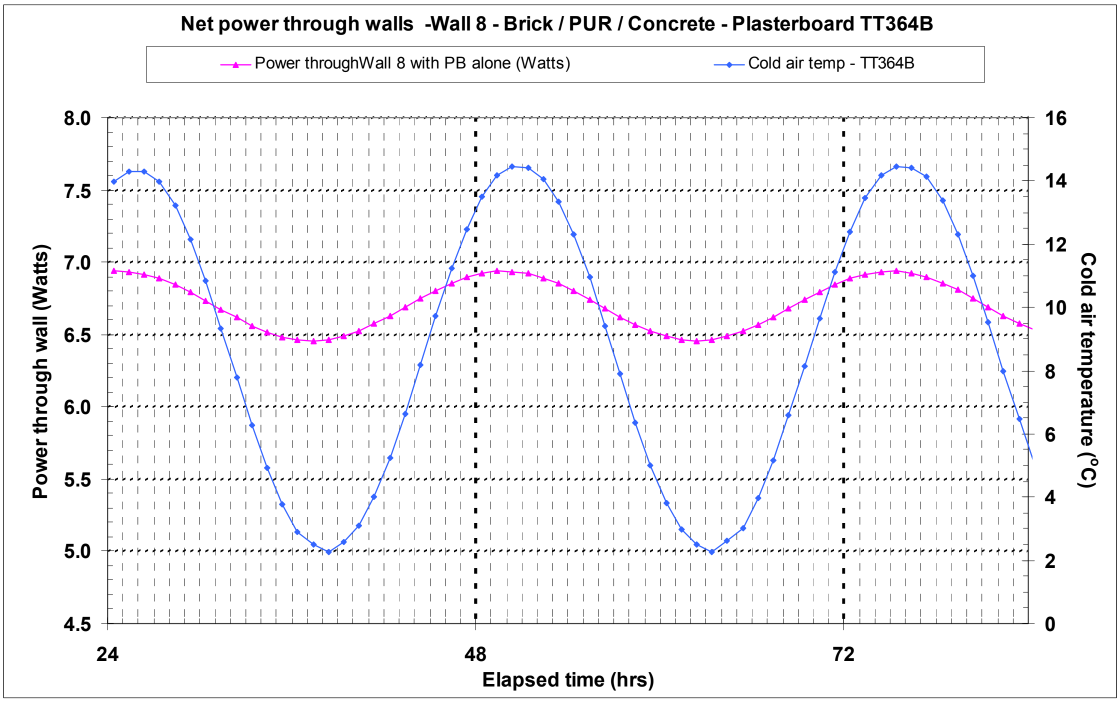
An equation relating power through the Wall + EPS for a given cold air temperature was also derived – see Figure 14.

Figure 14 Equation relating power to cold air temperature for the surround panel (synchronised to the phase of Wall 8)



The power through the wall alone was then obtained from these two equations – see Figure 15

Figure 15 Equation relating power to cold air temperature for Wall 8 and the surround panel.



Finally the energy in watt hours (Wh) required to maintain the warm chamber at 24.4 °C over one cycle was calculated by integrating the area under the graph of power against time for one cycle.

The power amplitude and time lag between the maximum temperature difference and maximum power through the wall was determined from these graphs.

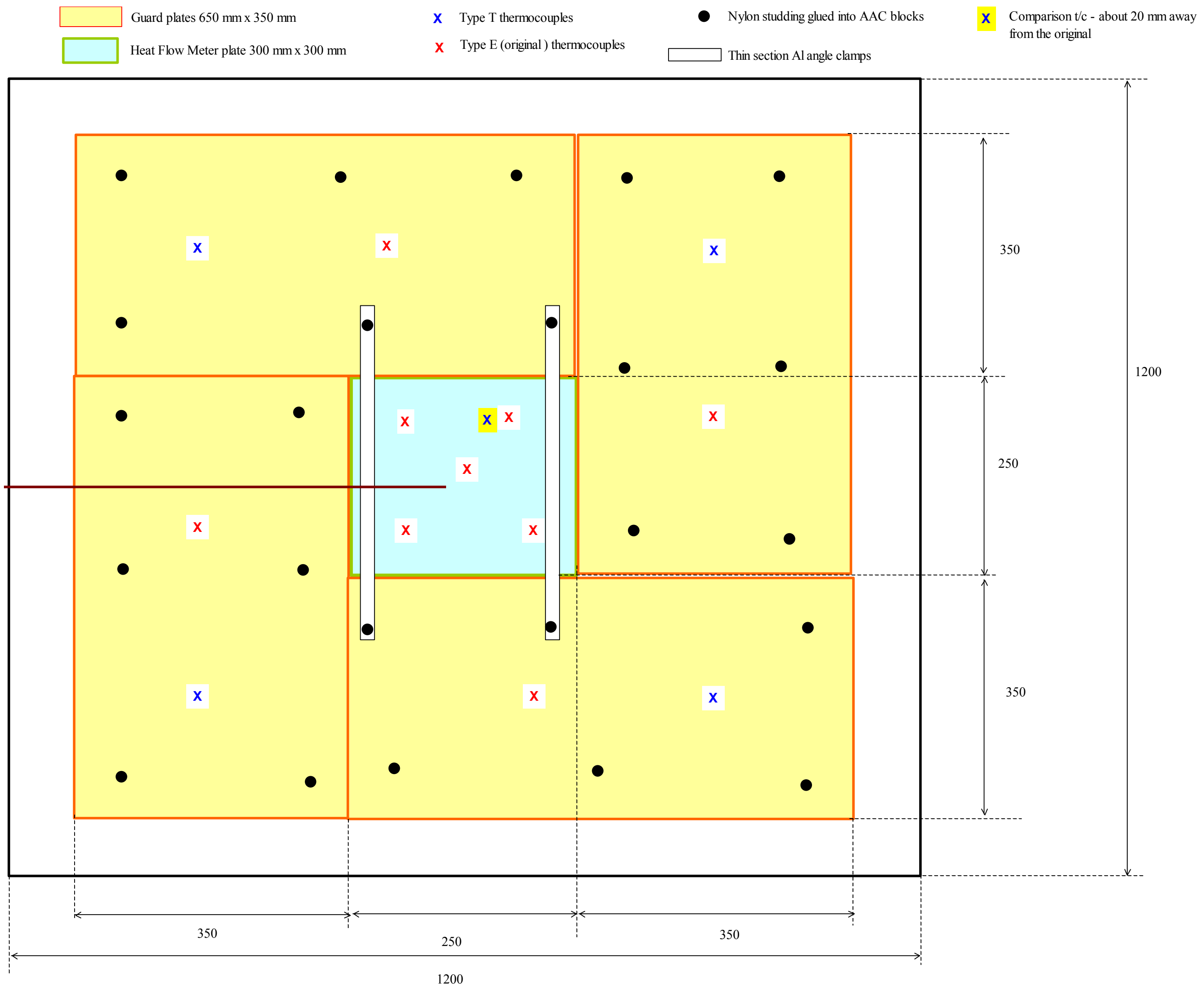
The time lag between the minimum temperature on the cold side and the minimum temperature on the warm side was determined by inspection of the data files.

5.2.2 Using the output of a HFM fixed to the wall surface

After the steady state measurement and cycling measurement without the HFM were completed the collar guard and wall were removed from the Hot Box apparatus and the HFM and guard plates fixed to the warm surface as shown in Figure 16. The HFM was mounted in the centre of each wall with thermocouples fixed to the wall beneath it as also shown in Figure 16.

The HFM ouput converted to power (W) using the calibration data produced by NPL using the 610 mm guarded hot plate apparatus. In this case there was no need to correct for the power being transferred through the surround panel. This value however only relates to the central 300 mm x 300 mm portion of the test wall. In the case of the timber frame wall (Wall 2) this was a problem as the HFM was site directly over the crossed studs and so gave quite different values from those obtained for the whole wall.

Figure 16 Drawing of heat flow meter and guard plates



6 RESULTS OF THE THERMAL PERFORMANCE MEASUREMENTS

6.1 RESULTS OF THE U-VALUE MEASUREMENTS.

These values are shown in Table 10 with the U-values calculated using i) Physibel VOLTRA, ii) the EN 6946 method.

6.2 ENERGY (WH) TO KEEP WARM CHAMBER AT 24 °C PER CYCLE.

This value was derived in two ways; i) using the power through the wall determined from the hot box power and ii) using the power determined from the output of the 0.3 m x 0.3 m HFM. A summary of both these values for each wall are shown in Table 10. The graphs of power through the wall plotted against elapsed time and the cold air temperature plotted against elapsed time for Wall 1, Wall 2, Wall 3, Wall 4, Wall 6, Wall 7 and Wall 8 are shown in Figures 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27 and 28 respectively.

6.3 TIME LAG – MAX TEMP. DIFF. AND MAX. POWER TRANSFER THROUGH THE WALL.

This value was derived in two ways; i) using the power through the wall determined from the hot box power and ii) using the power determined from the output of the 0.3 m x 0.3 m HFM. A summary of both these values for each wall are shown in Table 10. The graphs of power through the wall plotted against elapsed time and the cold air temperature plotted against elapsed time for Wall 1, Wall 2, Wall 3, Wall 4, Wall 6, Wall 7 and Wall 8 are shown in Figures 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27 and 28 respectively.

6.4 TIME LAG BETWEEN THE MIN. COLD TEMP. AND MIN. TEMP. ON THE WARM SIDE.

This was difficult to determine accurately as the variation in temperature on the warm side was very small. It was not obtained from the graphs but from the tables of data. A summary of these values for each wall is shown in Table 10.

6.5 AMPLITUDE OF THE POWER VARIATION RESULTING FROM TEMPERATURE CYCLING.

This value was derived in two ways; i) using the power through the wall determined from the hot box power and ii) using the power determined from the output of the 0.3 m x 0.3 m HFM. A summary of both these values for each wall are shown in Table 10. The graphs of power through the wall plotted against elapsed time and the cold air temperature plotted against elapsed time for Wall 1, Wall 2, Wall 3, Wall 4, Wall 6, Wall 7 and Wall 8 are shown in Figures 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27 and 28 respectively.

6.6 ROLLING AVERAGE OF U-VALUES DERIVED FROM CYCLING MEASUREMENTS.

During the thermal cycling the power through the wall cycles in response to the temperature difference variations. During these measurements this power was recorded every hour. Using these power values, the instantaneous thermal transmittance (or in the case where the output of the HFM was used, the instantaneous thermal conductance) was calculated. The rolling average of these instantaneous values approaches the steady state U-value after a sufficient period of time. This value was derived in two ways; i) using the power through the wall determined from the hot box power and ii) using the power determined from the output of the 0.25 m x 0.25 m HFM. The graphs showing the rolling average thermal conductance plotted against elapsed time are shown in Figures 29 to 35.

6.7 TEMPERATURE PROFILES THROUGH THE WALLS DURING CYCLING

The measured temperature profiles of Wall 1, Wall 2, Wall 3, Wall 4, Wall 6, Wall 7 and Wall 8 are shown in Figures 36 to 53.

Table 10 Measurement and calculations summary results table

Wall number	Test number	Wall description	Apparatus or calculation method	U-value - Meas & Calc.	Energy per 25 hr cycle over 12 °C (measured)	Amplitude of variation in power Meas.	Lag - Maximum temp diff to max power Meas.	Time constant of walls calculated with Voltra	Temp lag time	Ratio - Energy / U-value
				($W/m^2.K$)	(Whr)	(Watts)	(hrs)	(hrs)	(hrs)	($m^2.K.h$)
WALL 1	**TT369**	**ICF -** 9 mm thick ceramic floor tiles instead of Acrylic render / 65 mm 24 kg/m³ EPS on both sides & 150 mm thick 2400 kg/m³ concrete / plaster board (on 12 mm thick wood blocks) & STEEL connectors - **BUILT BY POLYSTEEL)**	Hot box	0.312	182	0.36	21.4		27.4	583
			HFM		178	0.24	10.0			571
			Voltra	0.252		0.12	12.0	98.0		
			EN 6946							
			ISO 13786						8.2	
WALL 2	**TT366**	**Timber frame** - 15 mm thick tongue & groove wood cladding. Wood studs (11% wood) 44 mm thick & 140 mm deep. Knauf Timber Slab glass fibre insulation between the studs & plaster board. **- BUILT BY NPL**	Hot box	0.266	153	2.38	4.8		2.5	576
			HFM		202	3.10	7.0			760
			Voltra	0.230		1.52	4.0	7.0		
			EN 6946							
			ISO 13786						3.8	
WALL 3	**TT363**	**"Standard" wall** - 102 mm Brick / 45 mm air cavity / 55 mm Celotex CW3055 foil faced PIR board/ 100 mm AAC / 10 mm air cavity / 12 mm plasterboard on 12 mm thick wood blocks/ 3 off st.st. wall ties **- BUILT BY NPL**	Hot box	0.279	157	0.65	11.0		9	562
			HFM		142	0.70	10.8			509
			Voltra	0.249		1.06	10.0	8.7		
			EN 6946	0.268						
			ISO 13786							
		Standard wall - 102 mm Brick / 45 mm air cavity / 55 mm foil faced PIR / 100 mm AAC / 10 mm air cavity / NO plasterboard - BUILT BY NPL	Hot box	0.285	170	1.65	11.0		6.0	595
			Voltra	0.263		1.57	9.5	6.3		
			EN 6946	0.276						
WALL 4	**TT371**	**ICF** - 9 mm thick ceramic floor tiles instead of Acrylic render / 65 mm NEOPOR Insulation on both sides & 150 mm thick 2400 kg/m³ concrete / plaster board (on 12 mm thick wood blocks) & STEEL connectors **- BUILT BY POLYSTEEL**	Hot box	0.283	170	0.32	22.3		24.3	601
			HFM		168	0.26	10.3			594
			Voltra	0.269		0.18	10.0	110		
			EN 6946							
			ISO 13786						8.3	
WALL 5		**NOT BUILT**								
WALL 6	**TT370**	**ICF** - 15 mm thick ceramic floor times instead of Acrylic render / 65 mm 24 kg/m³ EPS on both sides & 150 mm thick 2400 kg/m3 concrete / plaster board (on 12 mm thick wood blocks) & PLASTIC connectors - **BUILT BY POLYSTEEL**	Hot box	0.279	159	0.40	21.5		24.5	571
			HFM		157	0.16	10.2			561
			Voltra	0.232		0.12	10.0	106		
			EN 6946							
			ISO 13786						8.2	
WALL 7	**TT368**	**APA wall** - 15 mm thick ceramic floor tiles instead of Acrylic render / 80 mm insulation (55 mm + 25 mm) Celotex foil faced PIR board/ 200 mm thick AAC block / air cavity / plasterboard on 12 mm thick wood blocks.	Hot box	0.216	123	0.33	16.6		12.3	569
			HFM		118	0.39	12.5			545
			Voltra	0.176		0.37	10.0	24.4		
			EN 6946							
			ISO 13786						10.3	
WALL 8	**TT364**	**Concrete Centre** - Brick/cavity/ 55 mm Celotex CW3055 foil faced PIR board /lightweight agregate concrete/ air cavity / 12 mm plasterboard - **BUILT BY NPL**	Hot box	0.297	167	0.47	11.8		10.0	564
			HFM		160	0.75	10.6			540
			Voltra	0.280		0.51	11.0	15.0	11.0	
			EN 6946	0.302						
			ISO 13786		160	0.75				
		Concrete Centre - Brick/cavity/55 mm foil faced PIR board /lightweight agregate concrete/ air cavity / NO plasterboard	Hot box	0.321	182	1.03	9.0		7.5	568
			EN 6946	0.312						

Figure 17 Wall 1 – Power through wall (hot box) and cold air temperature vs time.

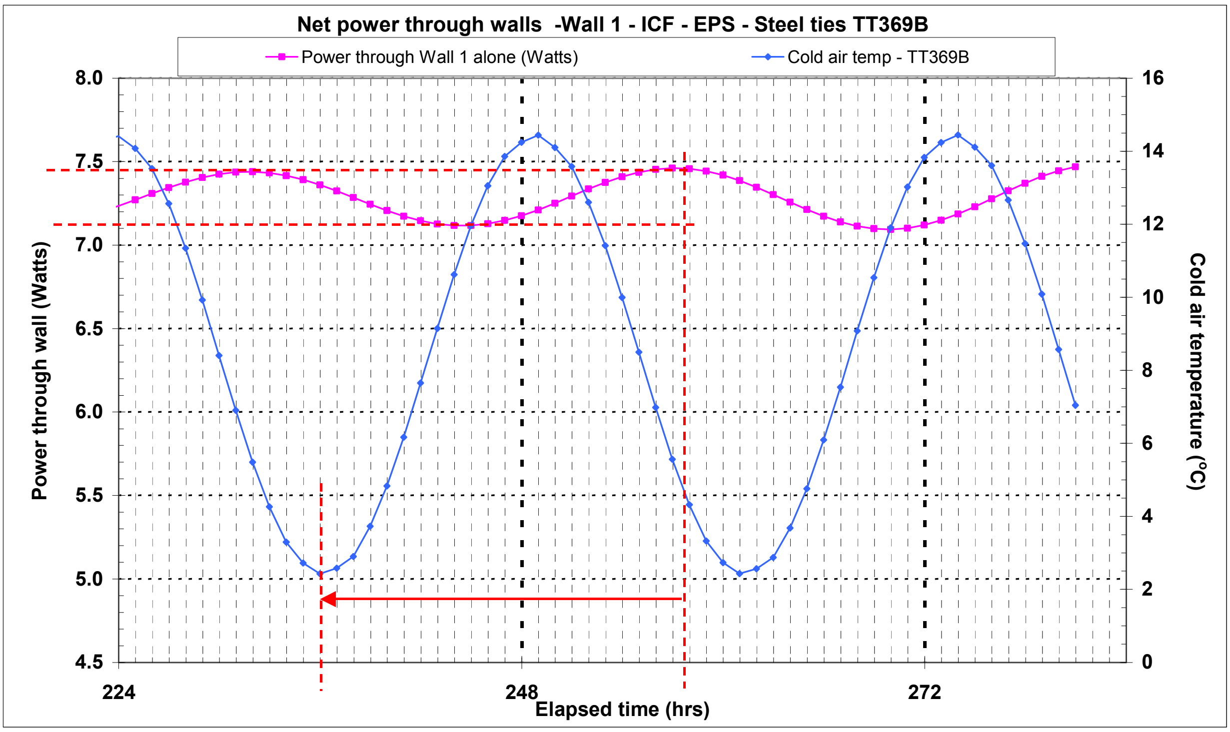


Figure 18 Wall 1 – Power through wall (HFM) and cold air temperature vs time

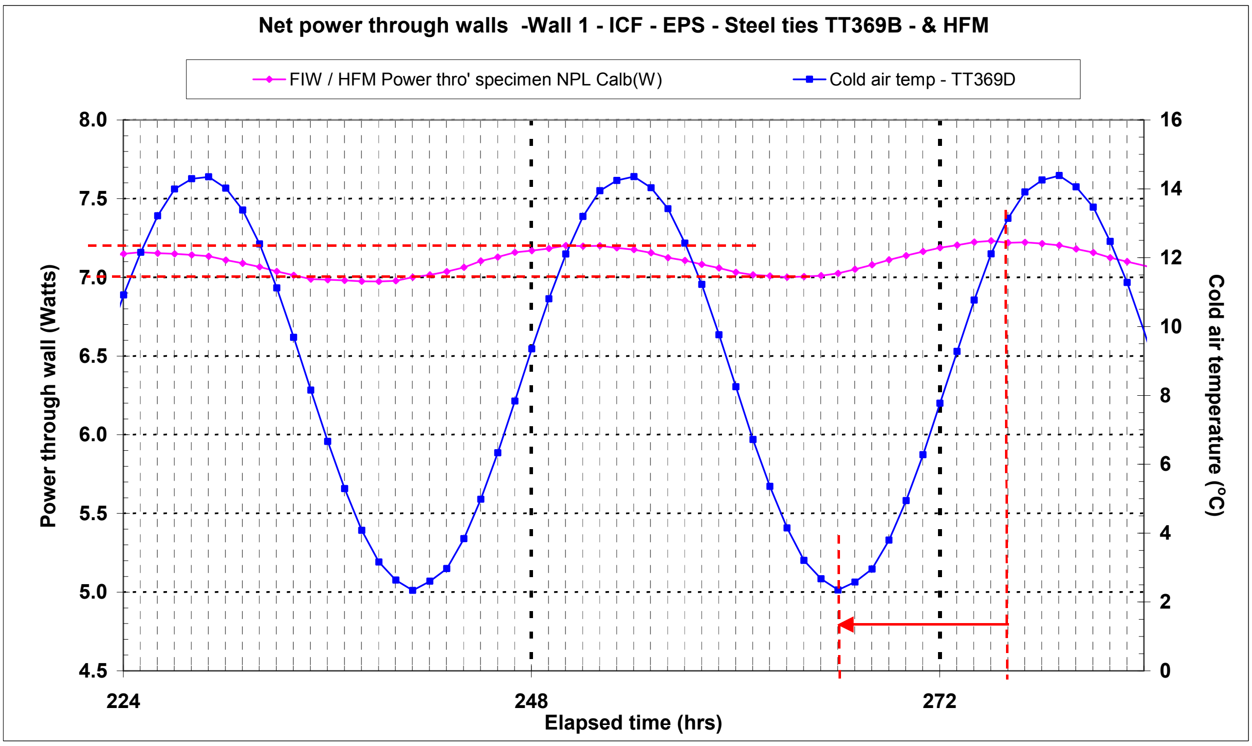


Figure 19 Wall 2 - Power through wall (hot box) and cold air temperature vs time

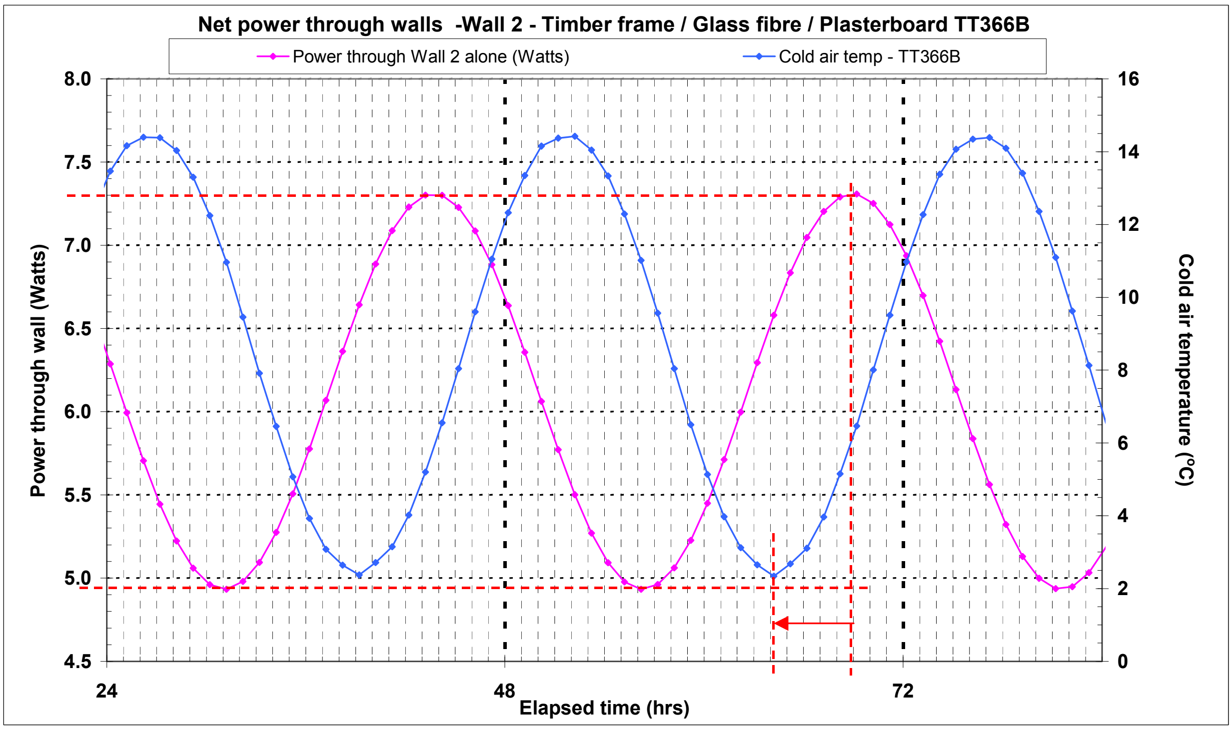


Figure 20 Wall 2 - Power through wall (HFM) and cold air temperature vs time

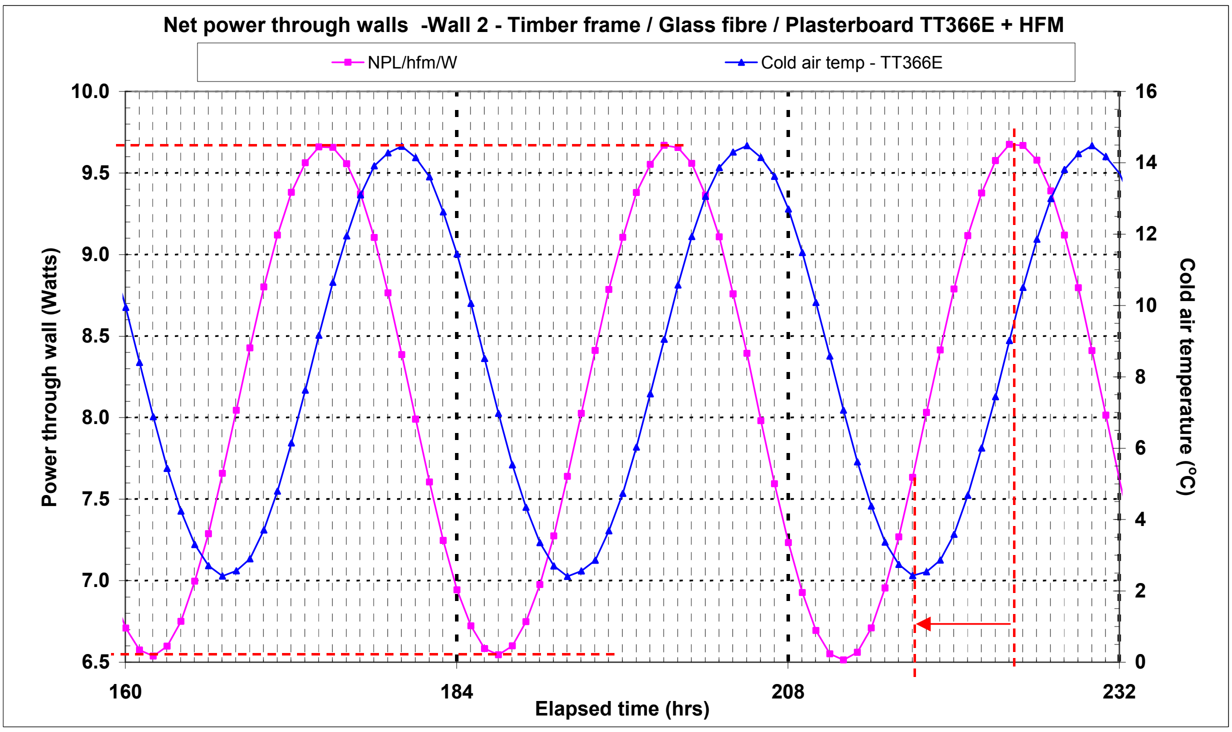


Figure 21 Wall 3 - Power through wall (hot box) and cold air temperature vs time

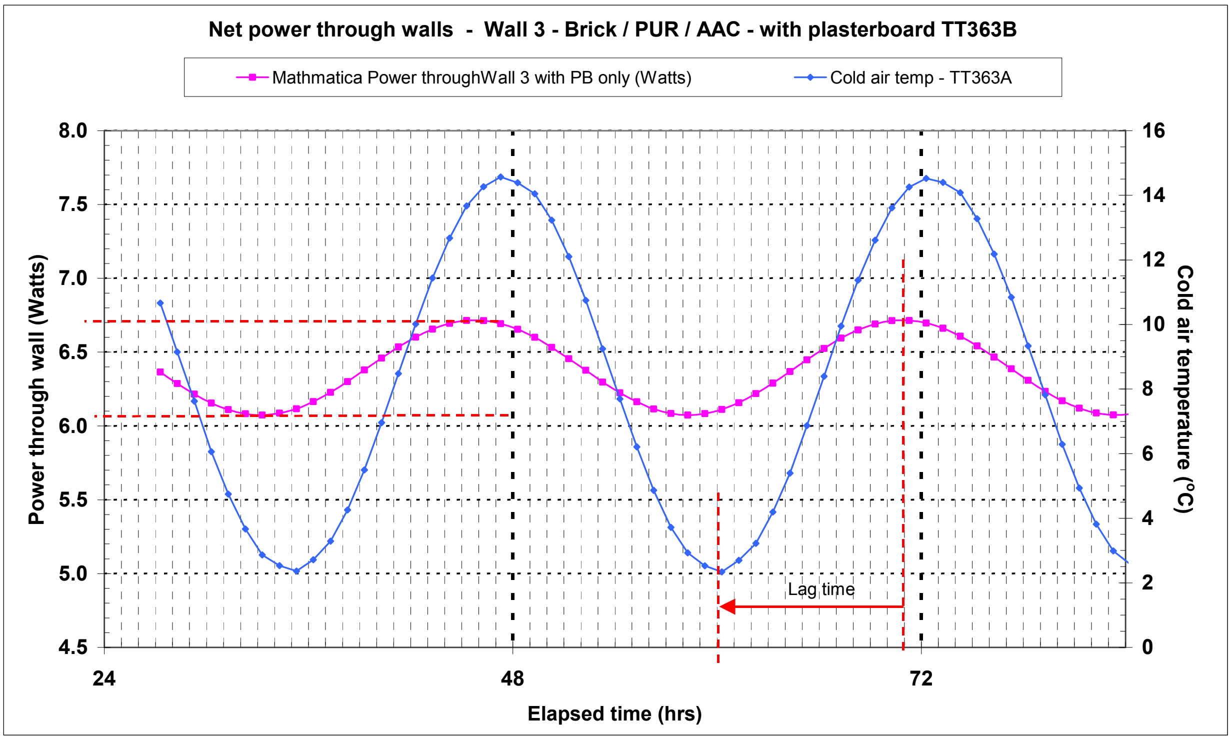


Figure 22 Wall 3 - Power through wall (HFM) and cold air temperature vs time

ca

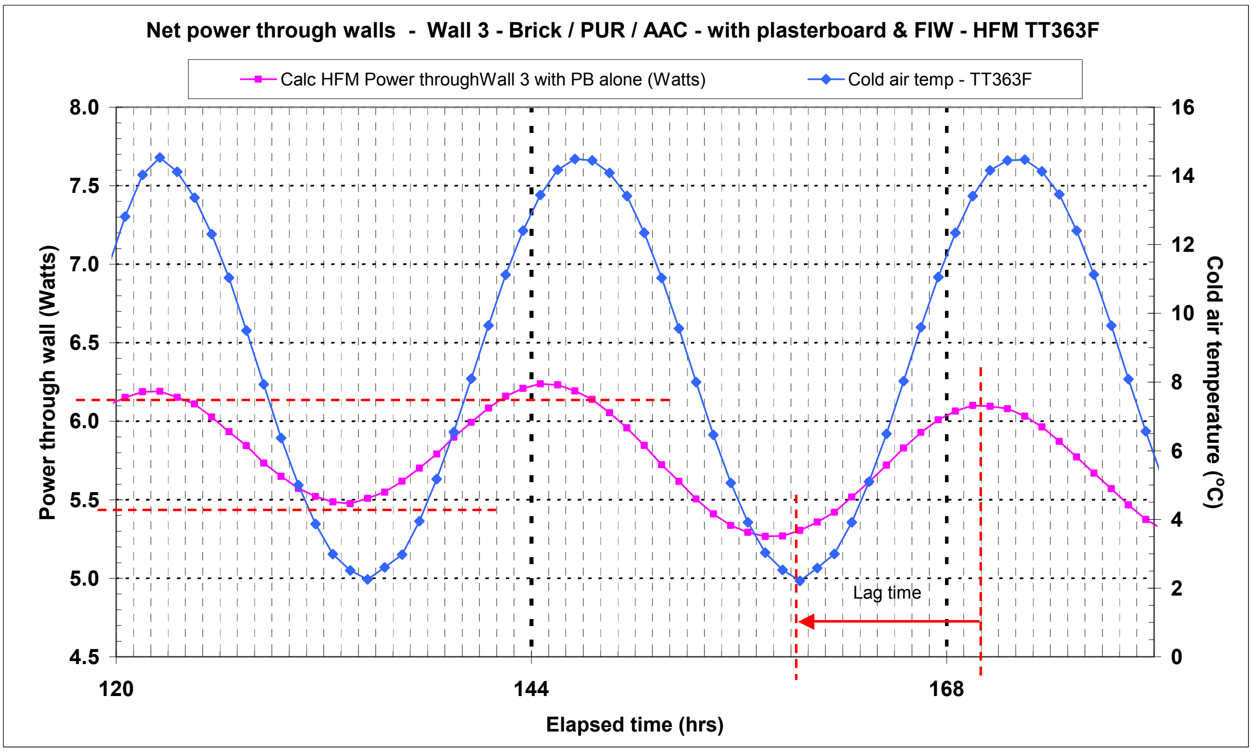


Figure 23 Wall 4 - Power through wall (hot box) and cold air temperature vs time

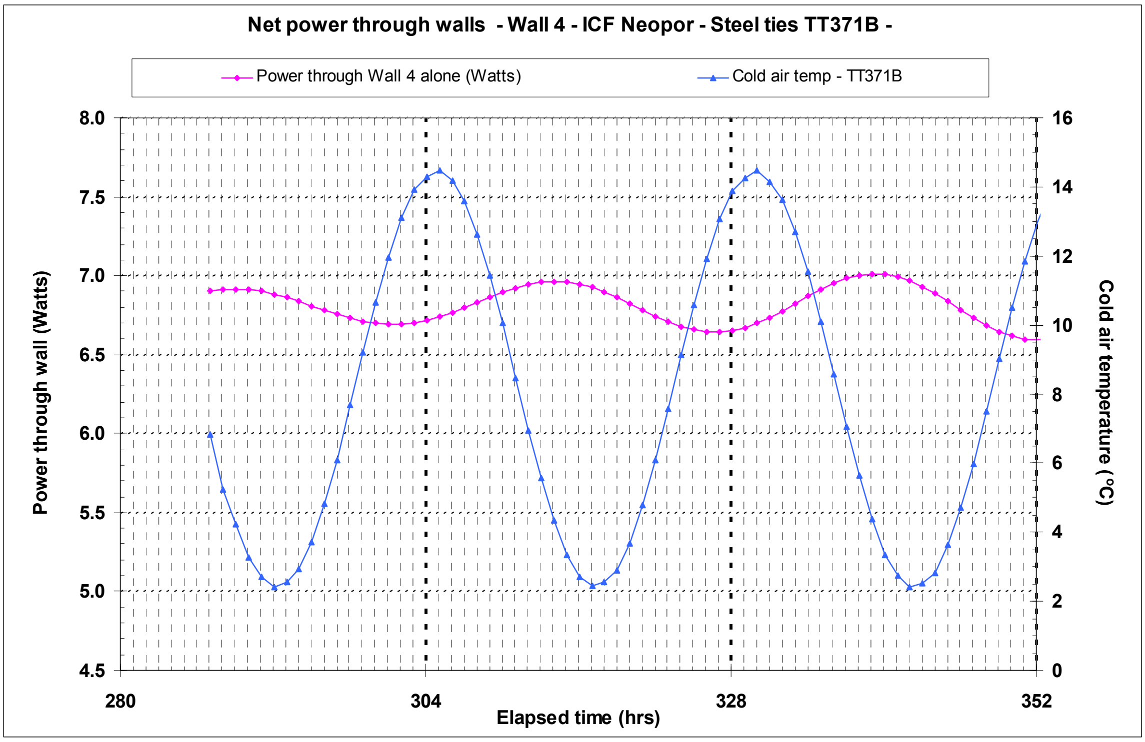


Figure 24 Wall 4 - Power through wall (HFM) and cold air temperature vs time

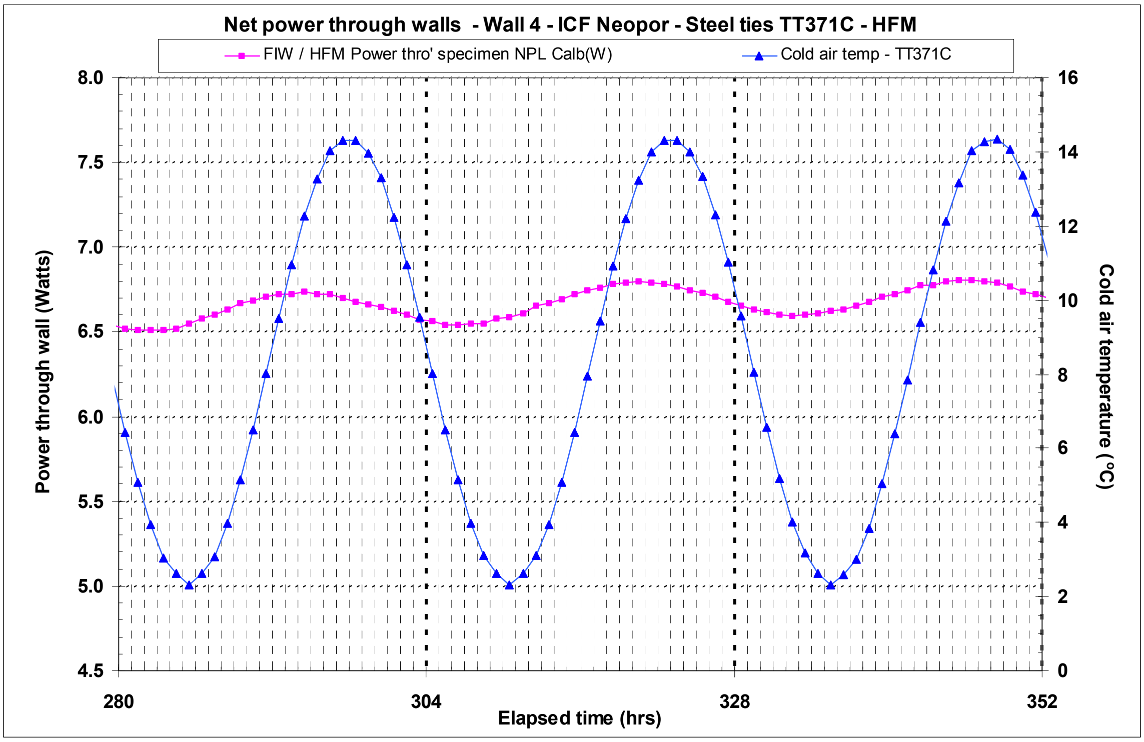


Figure 25 Wall 6 - Power though wall (hot box) and cold air temperature vs time

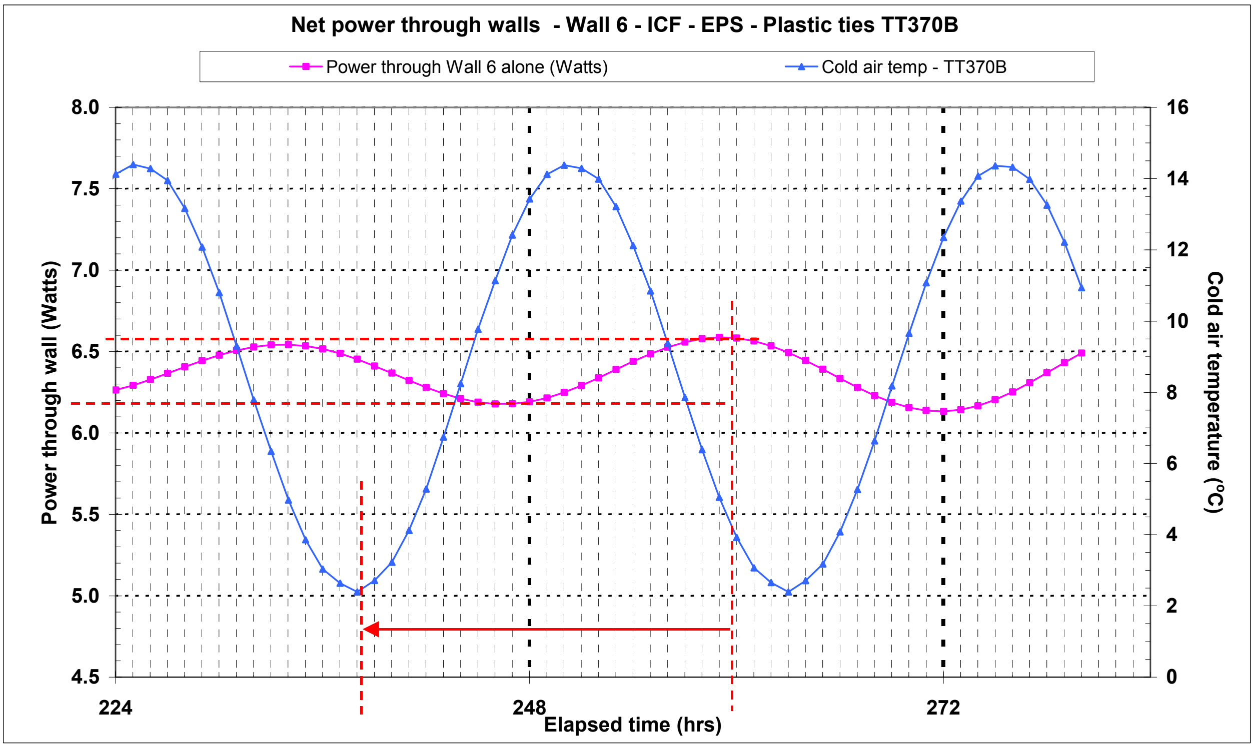


Figure 26 Wall 6 - Power though wall (HFM) and cold air temperature vs time

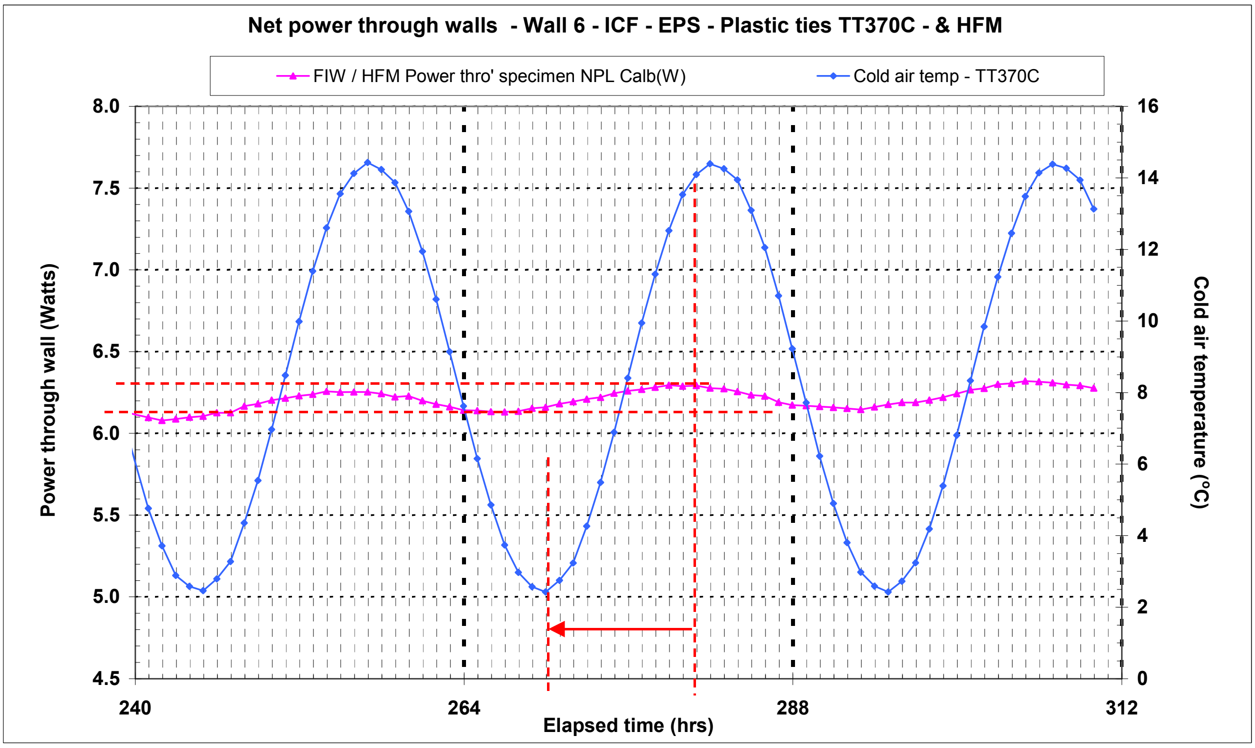


Figure 27 Wall 7 - Power through wall (hot box) and cold air temperature vs time

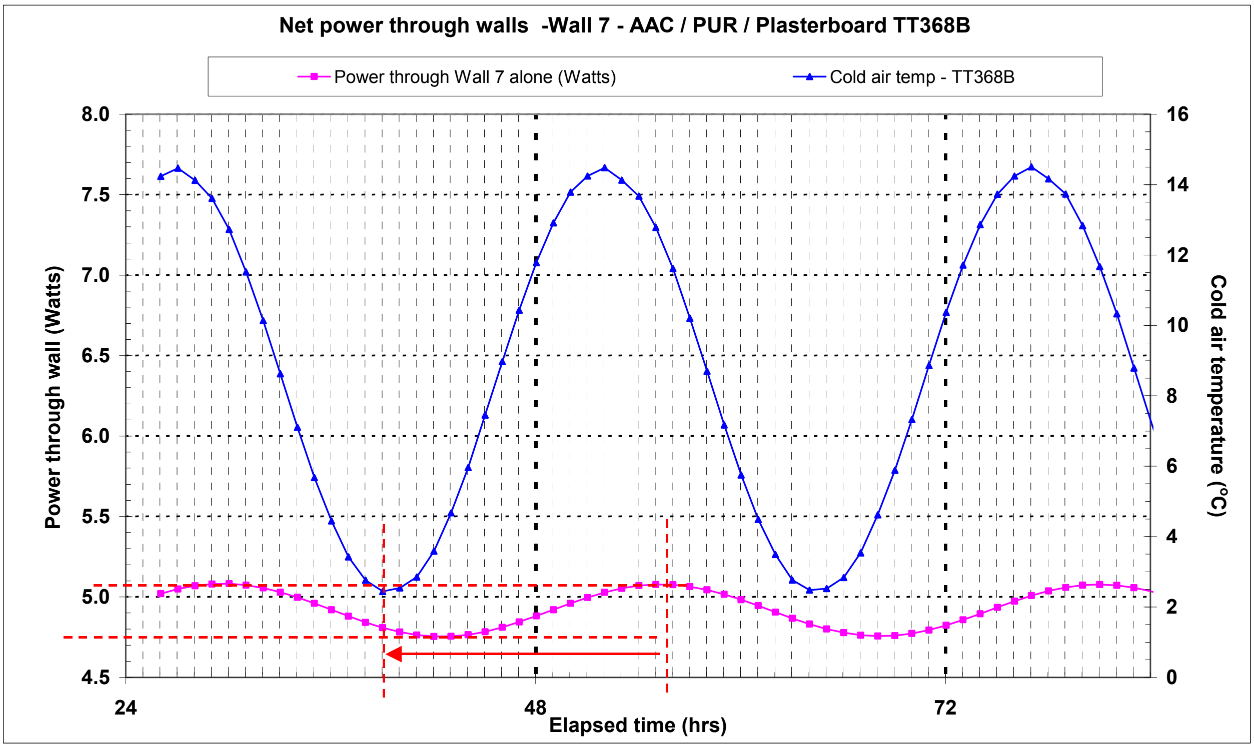


Figure 28 Wall 7 - Power through wall (HFM) and cold air temperature vs time

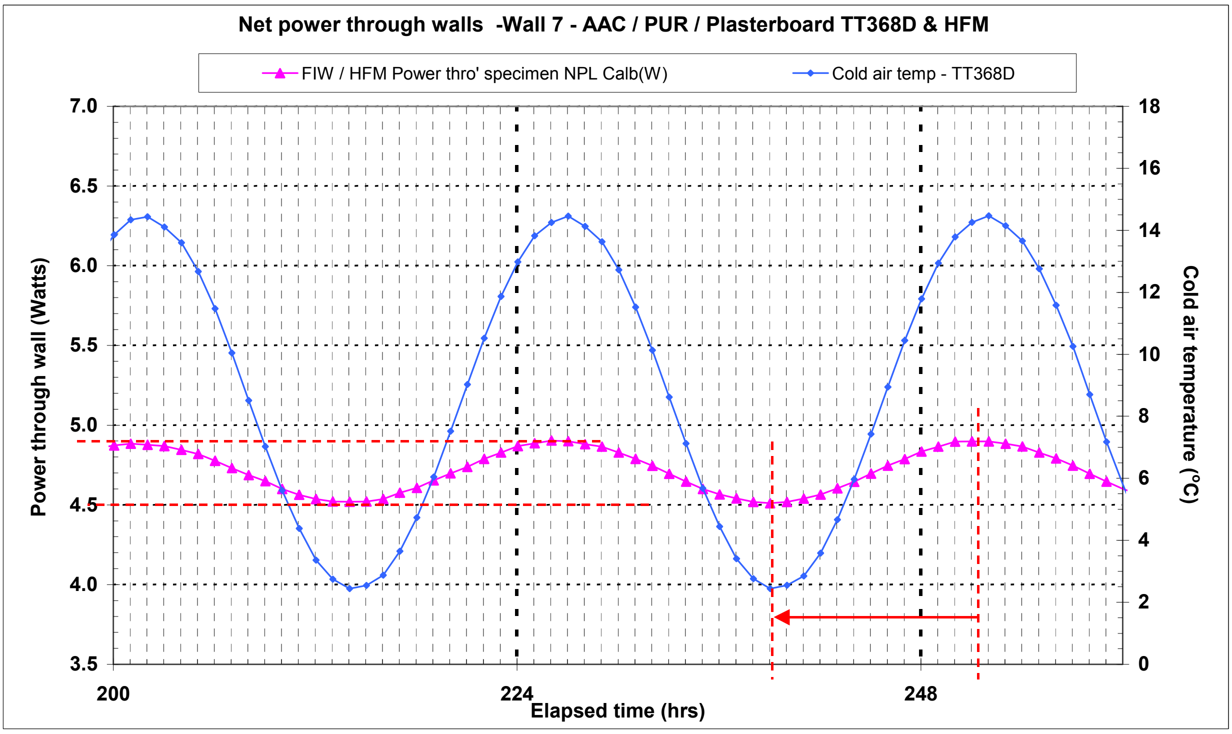


Figure 29 Wall 8 - Power through wall (hot box) and cold air temperature vs time

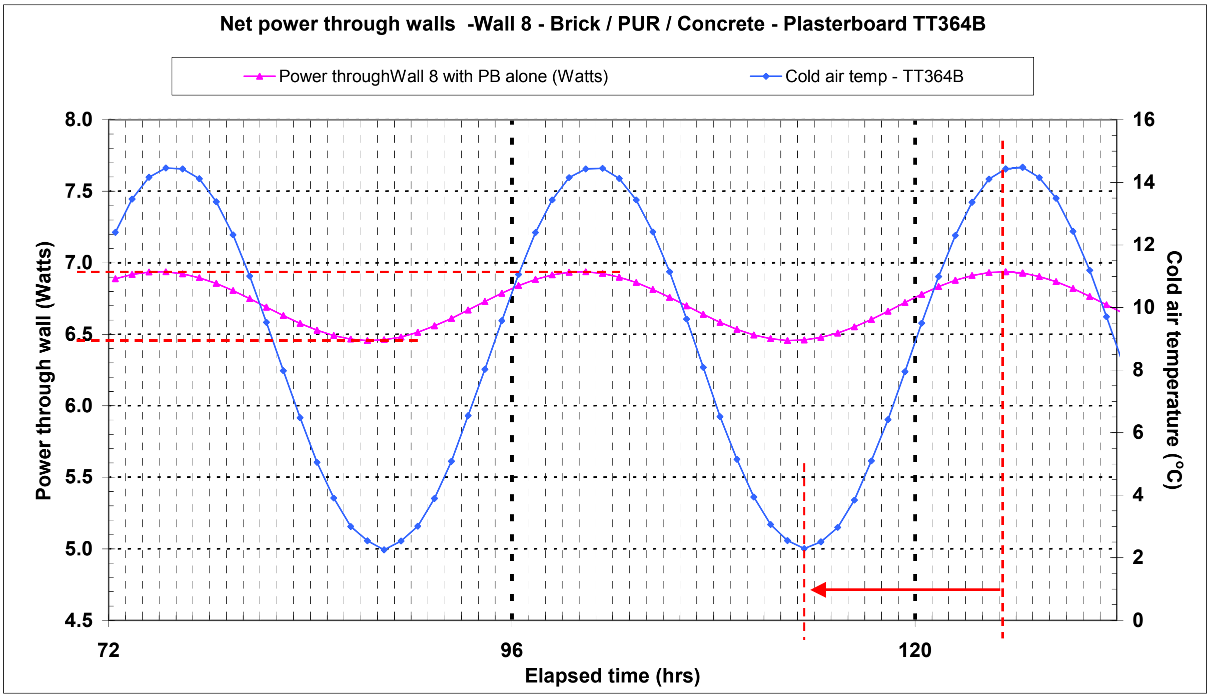


Figure 30 Wall 8 - Power through wall (HFM) and cold air temperature vs time

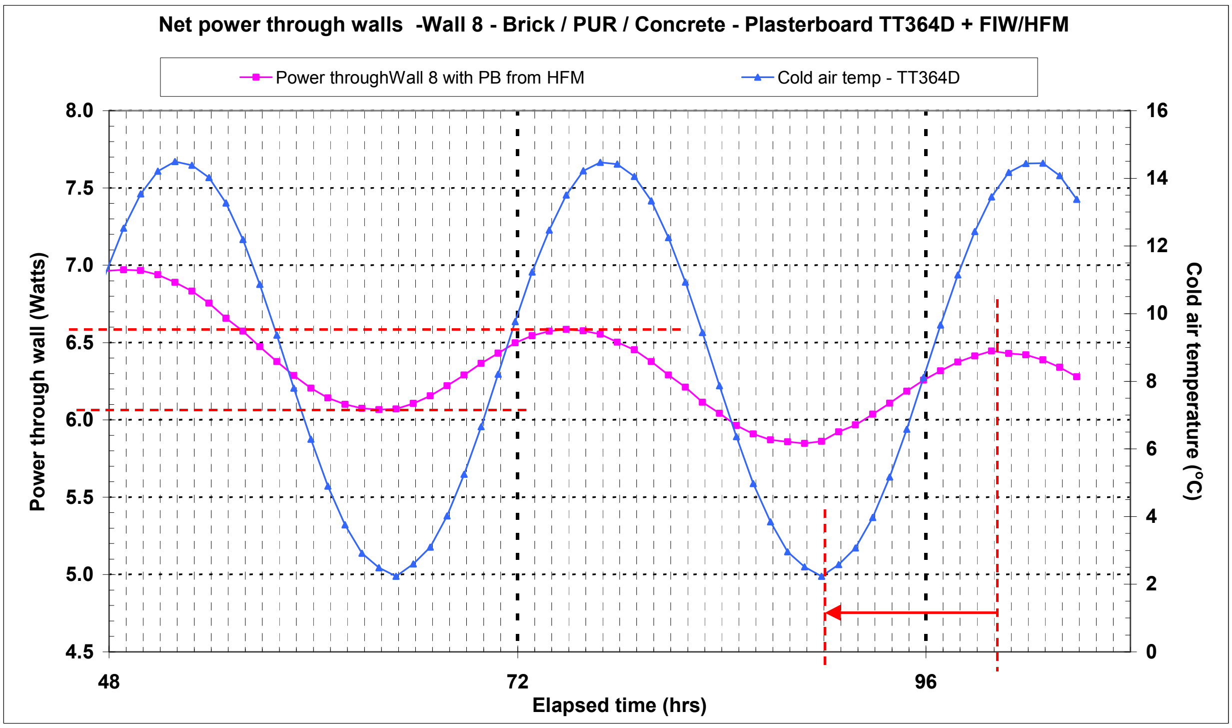


Figure 31 Wall 1 (TT369) - Rolling average thermal conductance

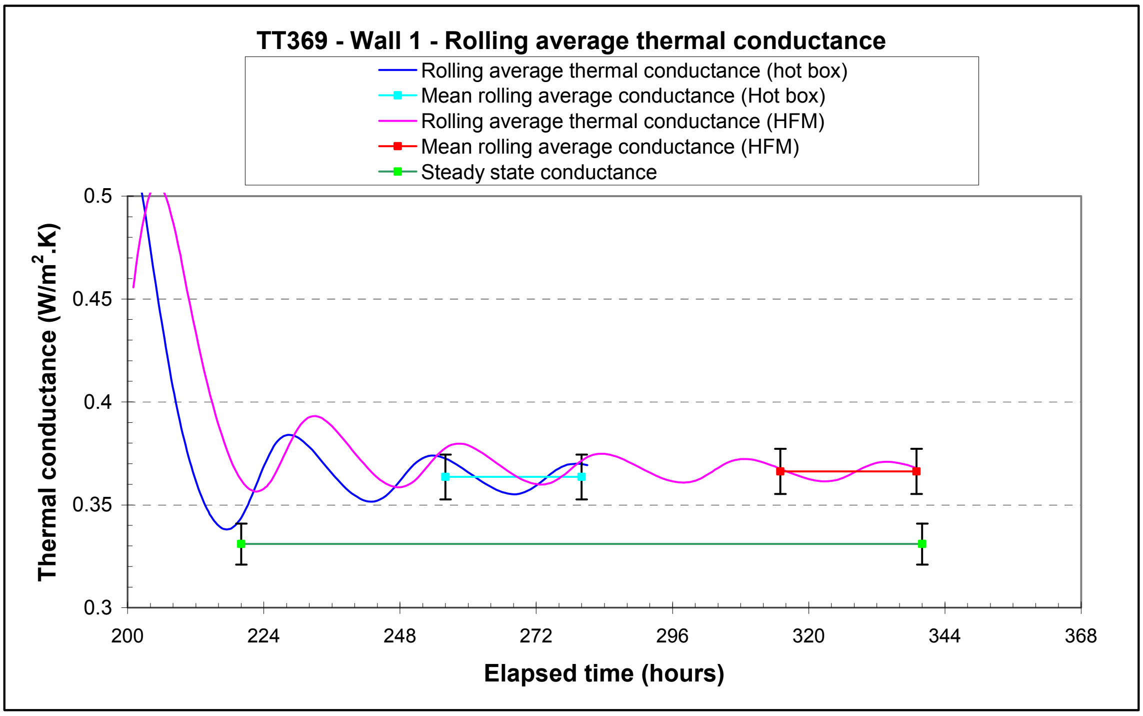


Figure 32 Wall 2 (TT366) - Rolling average thermal conductance

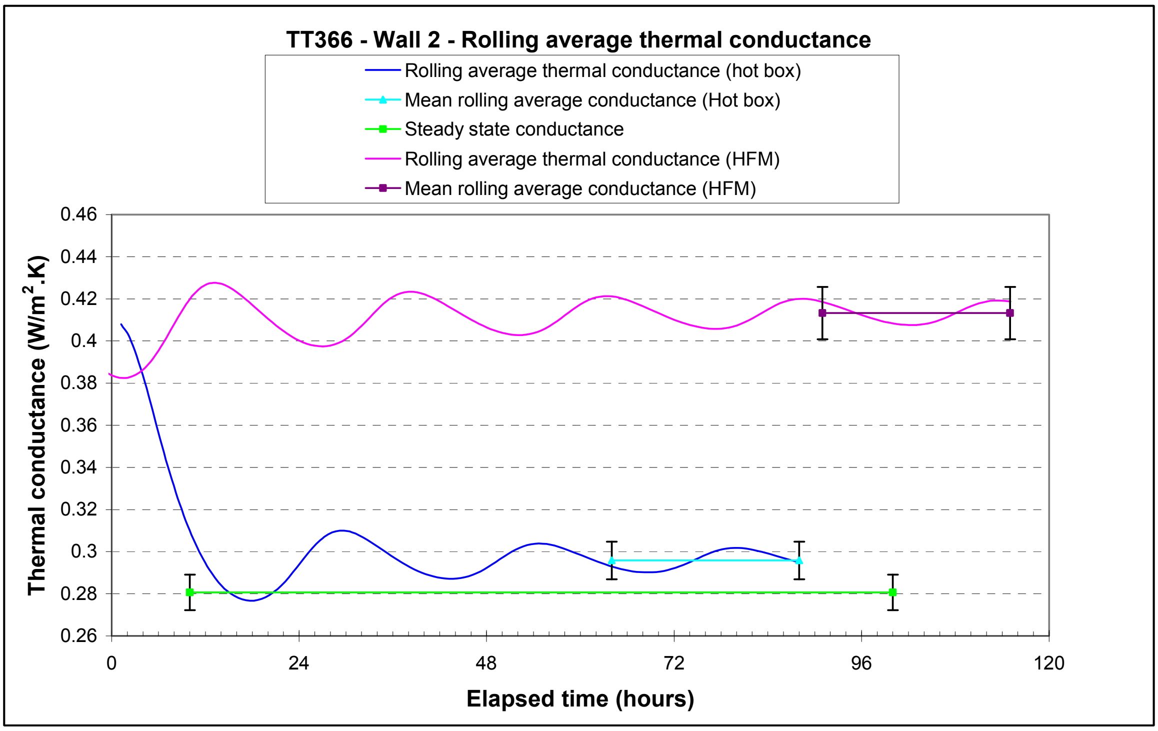


Figure 33 Wall 3 (TT363) -b Rolling average thermal conductance

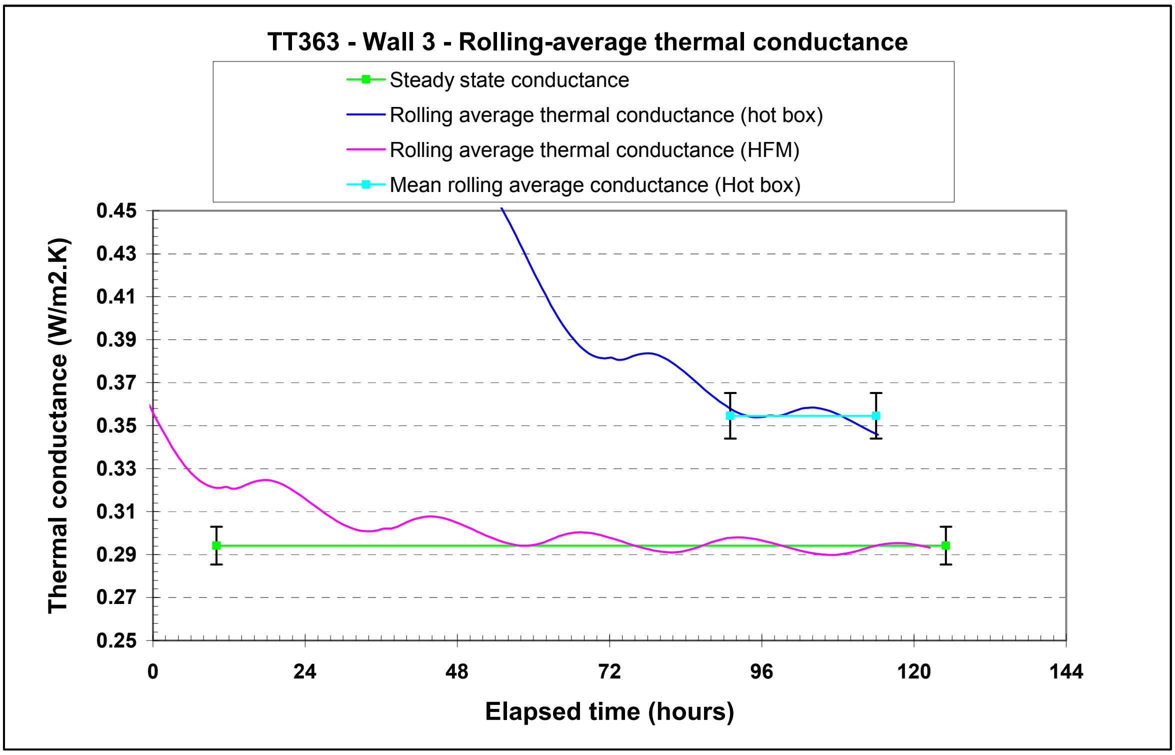


Figure 34 Wall 4 (TT371) - Rolling average thermal conductance

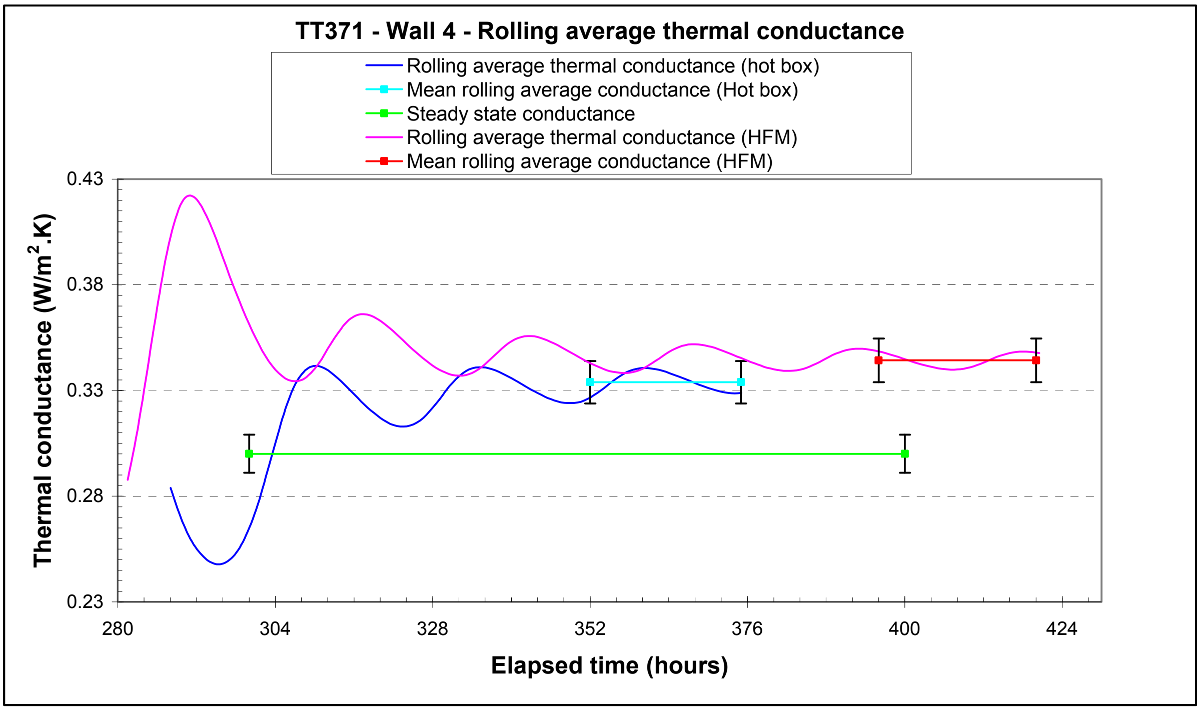


Figure 35 Wall 6 (TT370) - Rolling average thermal conductance

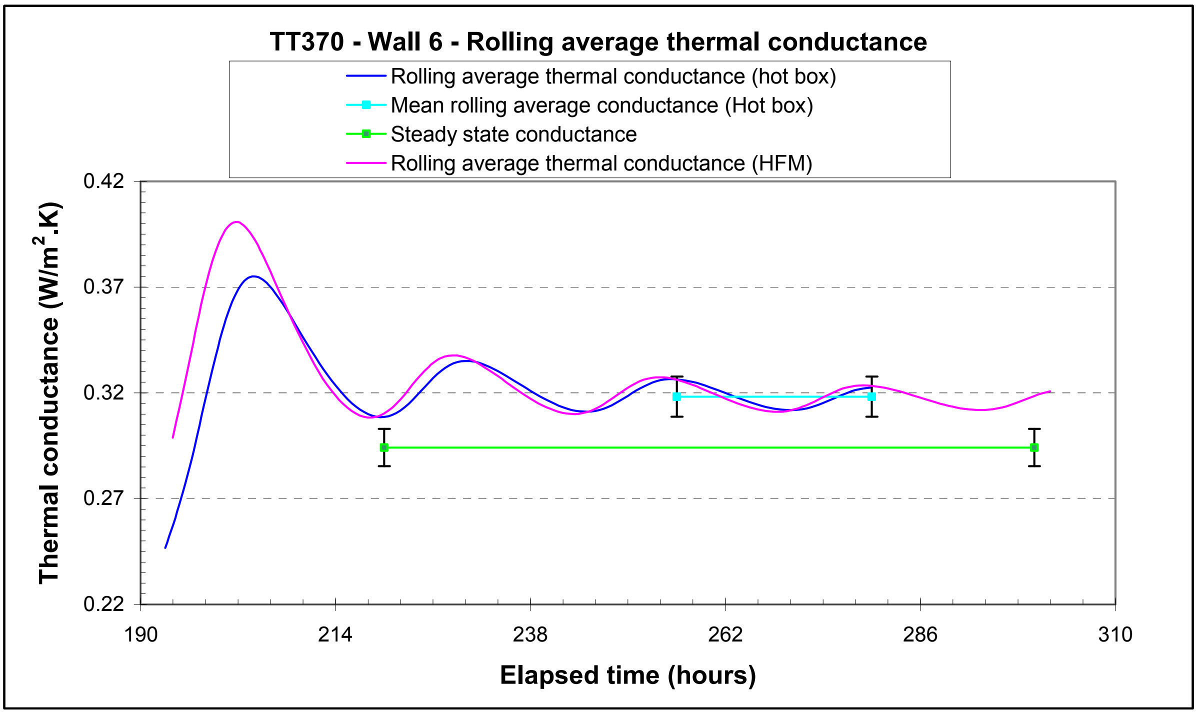


Figure 36 Wall 7 (TT368) - Rolling average thermal conductance

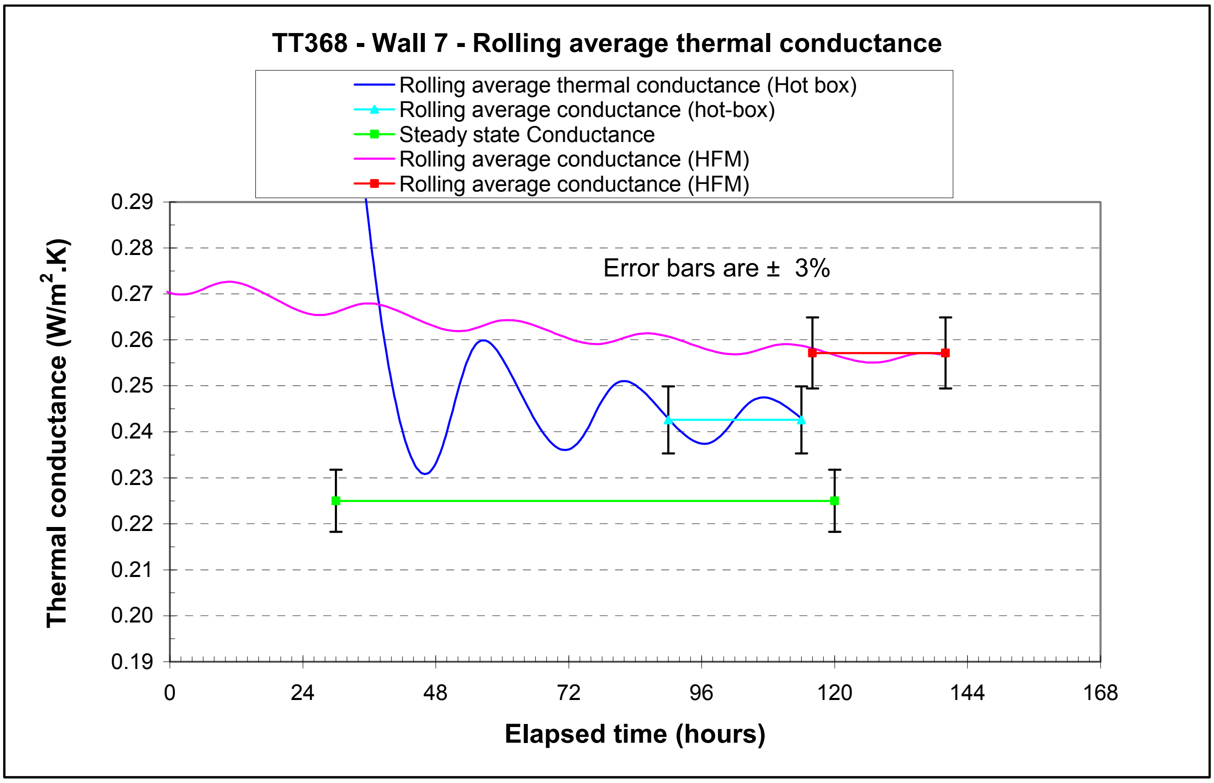


Figure 37 Wall 8 (TT364) - Rolling average thermal conductance.

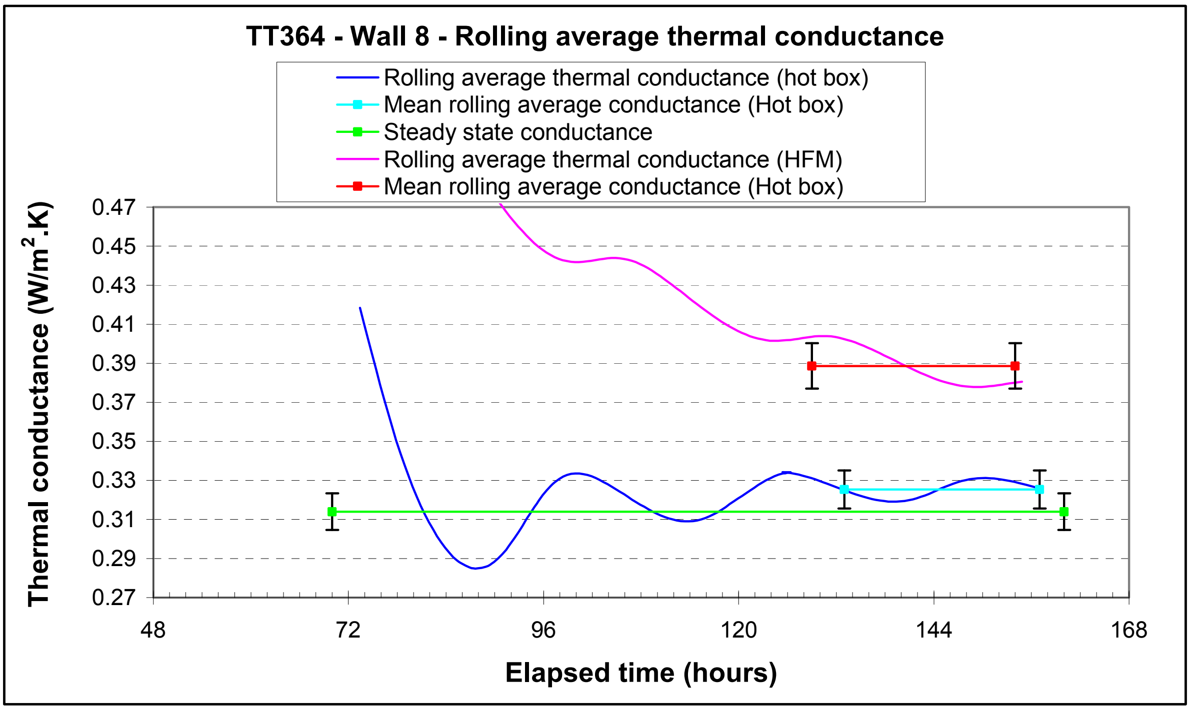
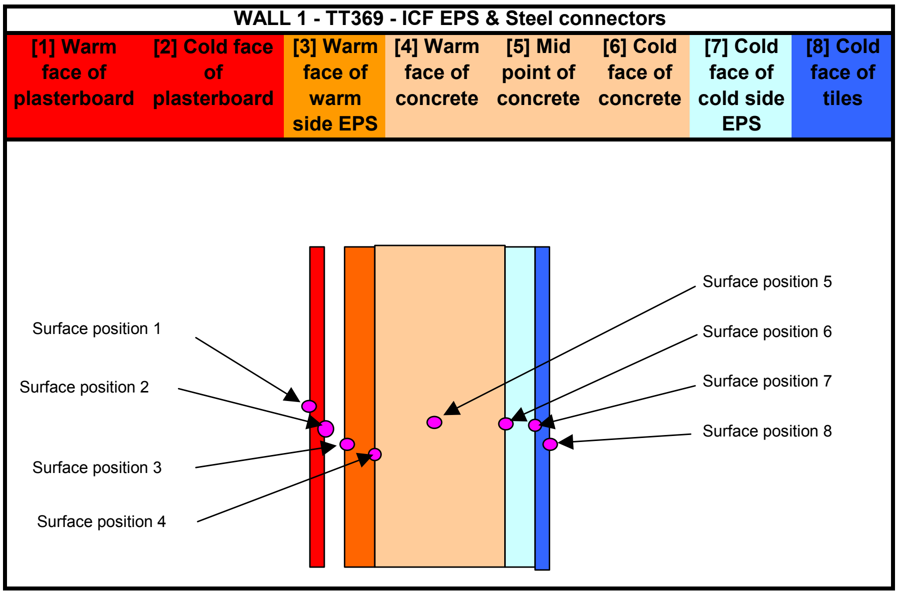
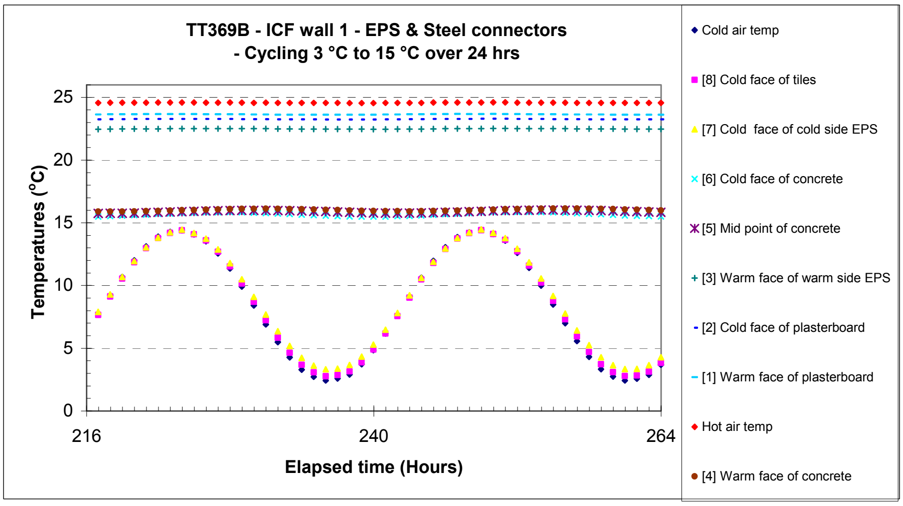


Figure 38 Wall 1 (TT369) - Temperature profiles





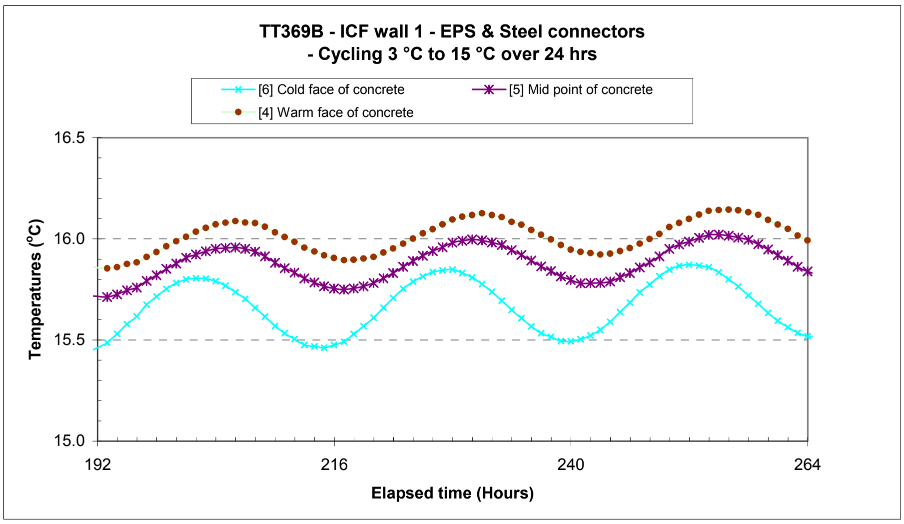


Figure 39 Wall 2 (TT366) – Thermocouple positions – Insulation & Studding stacks

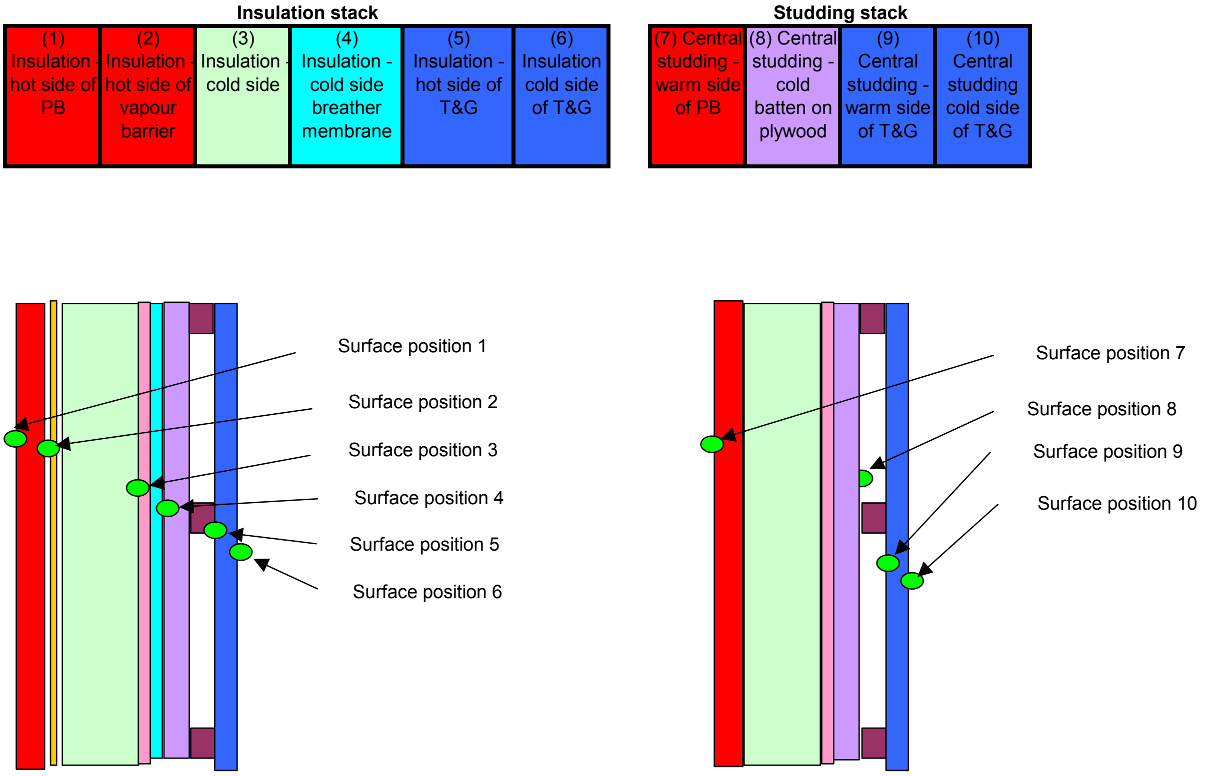
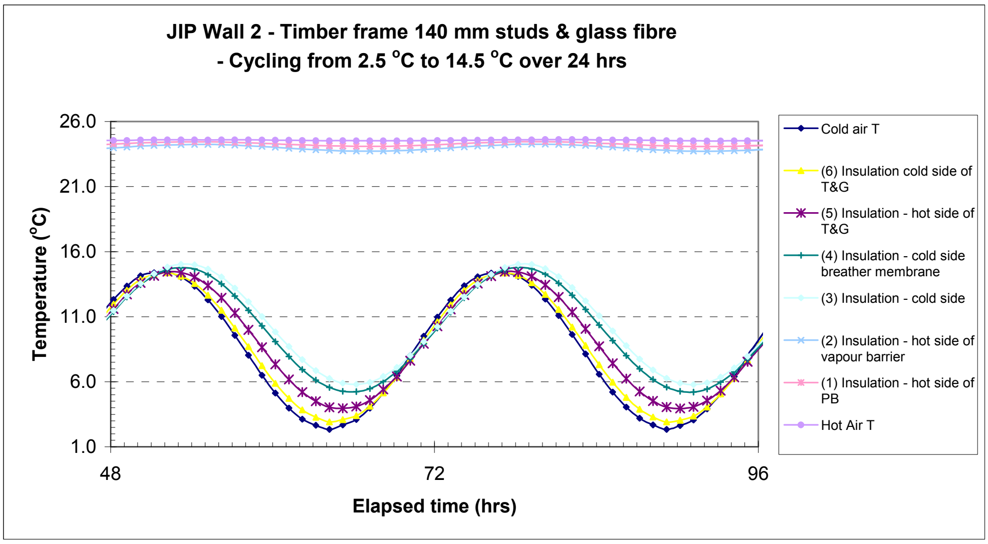
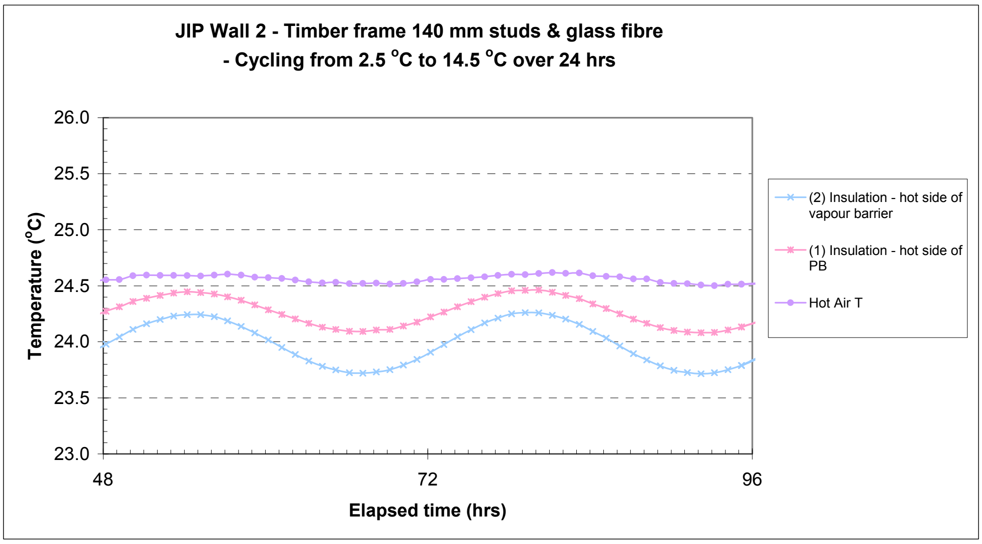


Figure 40 Wall 2 - Temperature profile - Insulation stack





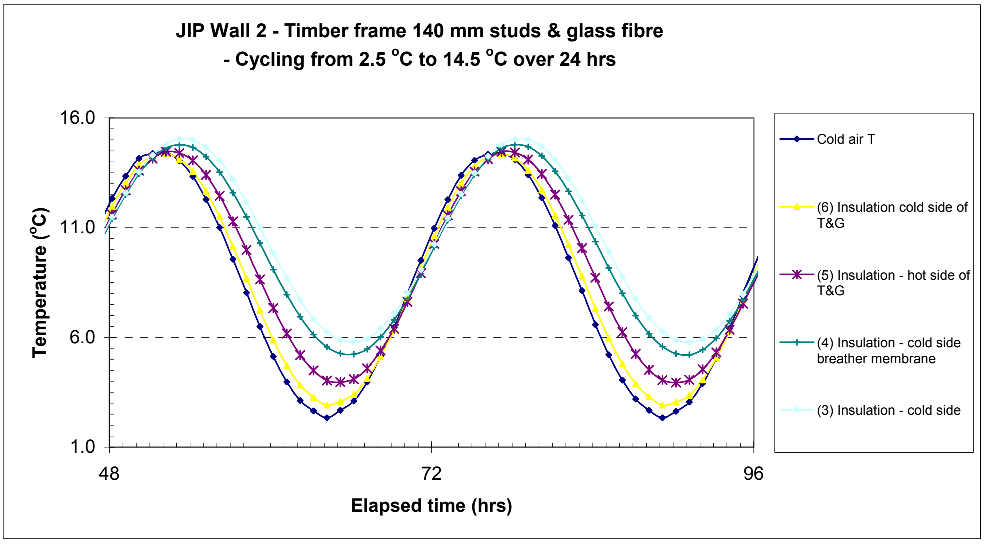
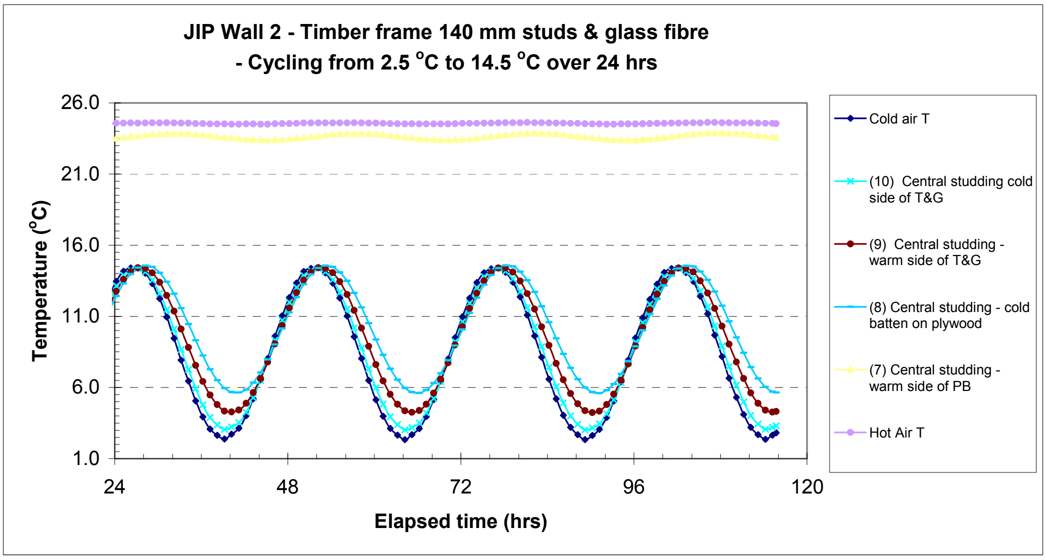
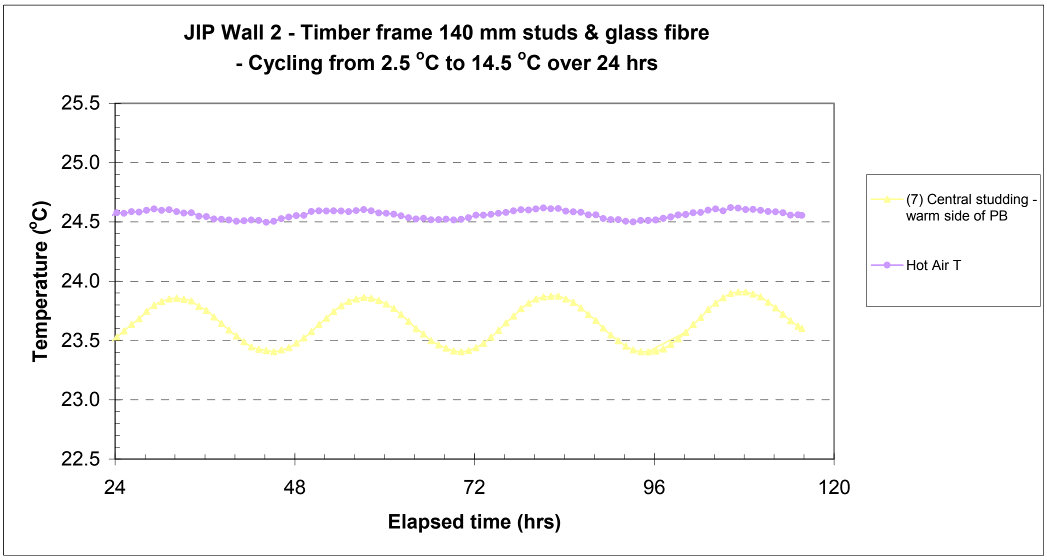


Figure 41 Wall 2 - Temperature profiles - Studding stack





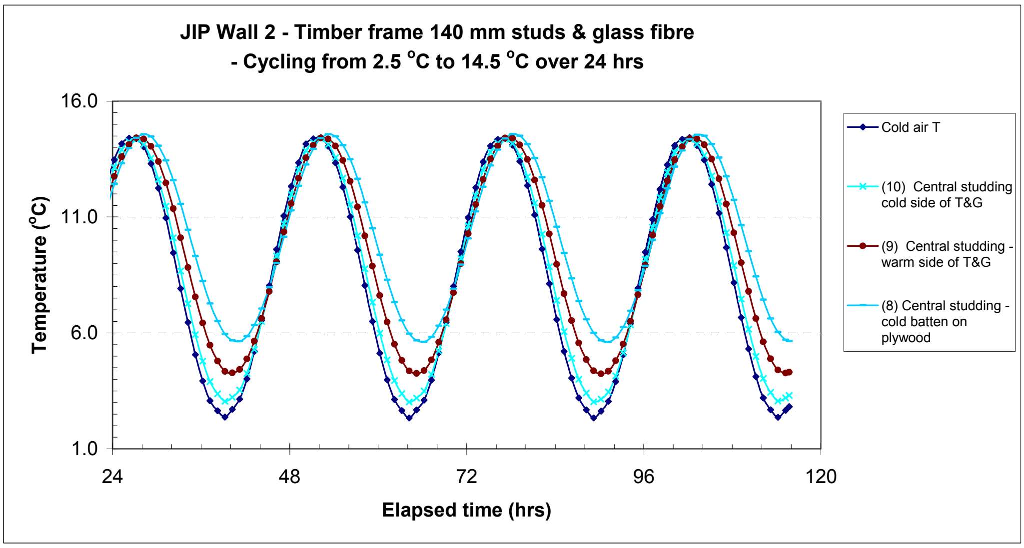


Figure 42 Wall 3 + Plaster board (TT363) - Thermocouple positions

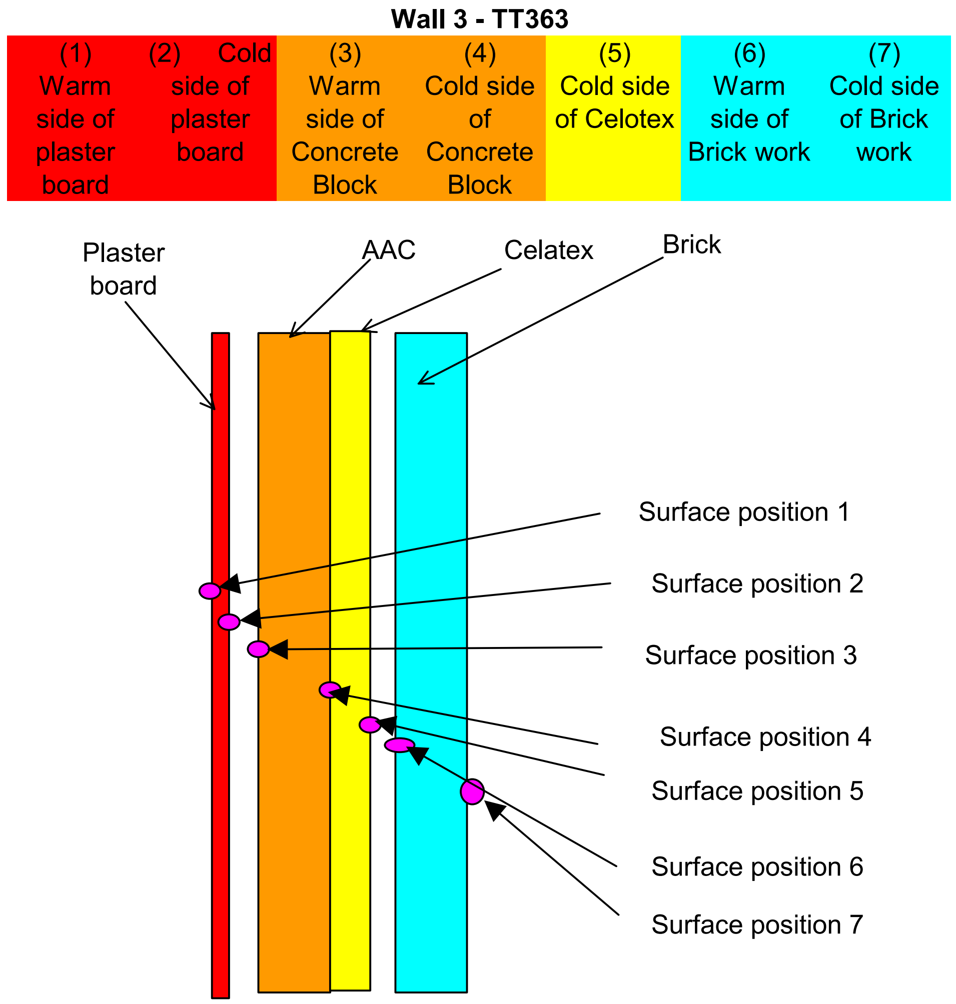
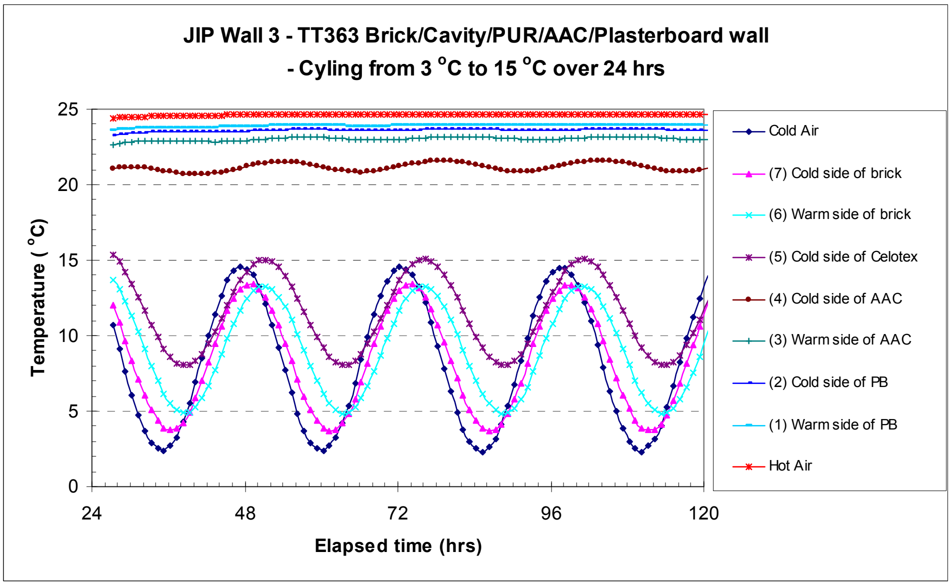
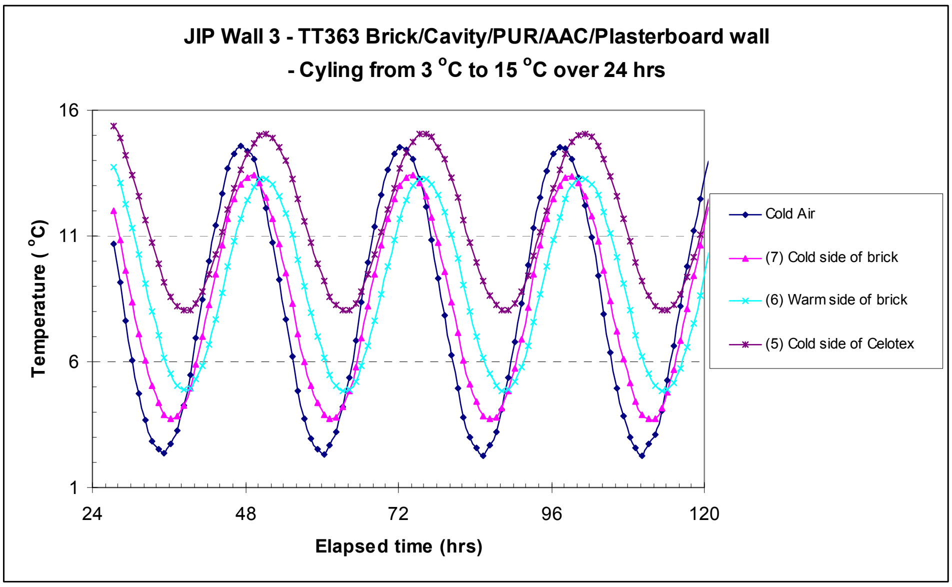


Figure 43 Wall 3 + Plasterboard Temperature profiles





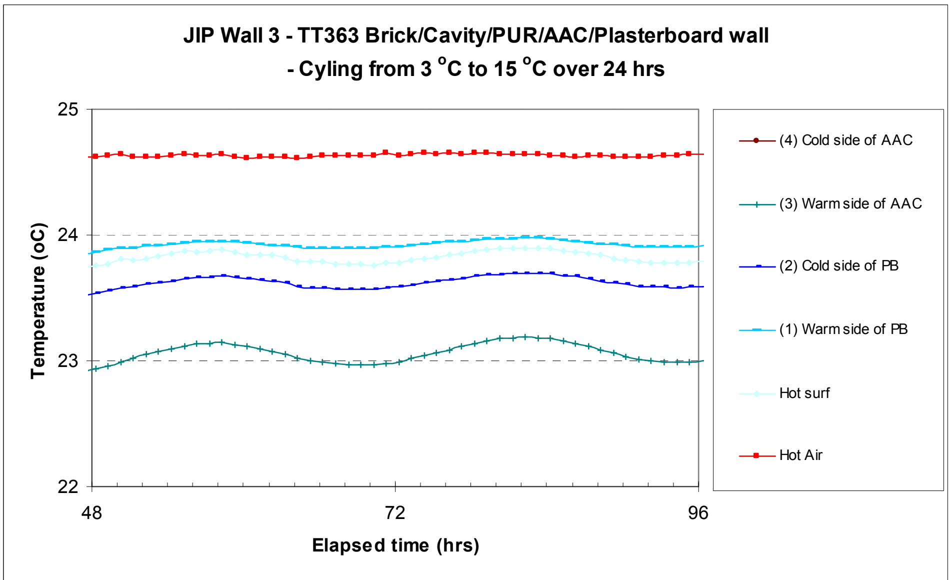


Figure 44 Wall 3 - No Plasterboard - Thermocouple positions

(1) Warm side of AAC	(2) Cold side of AAC	(3) Cold side of Celotex	(4) Warm side of brick	(5) Cold side of brick

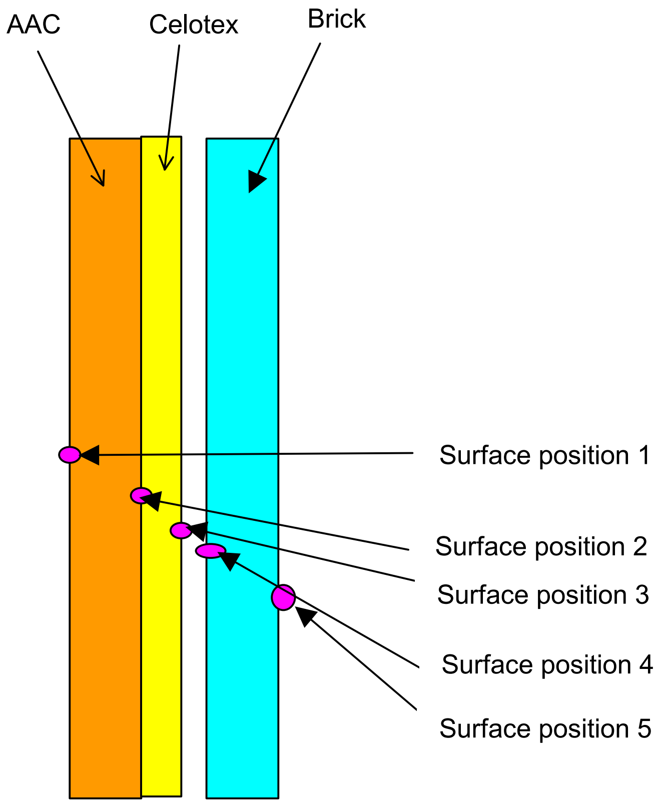
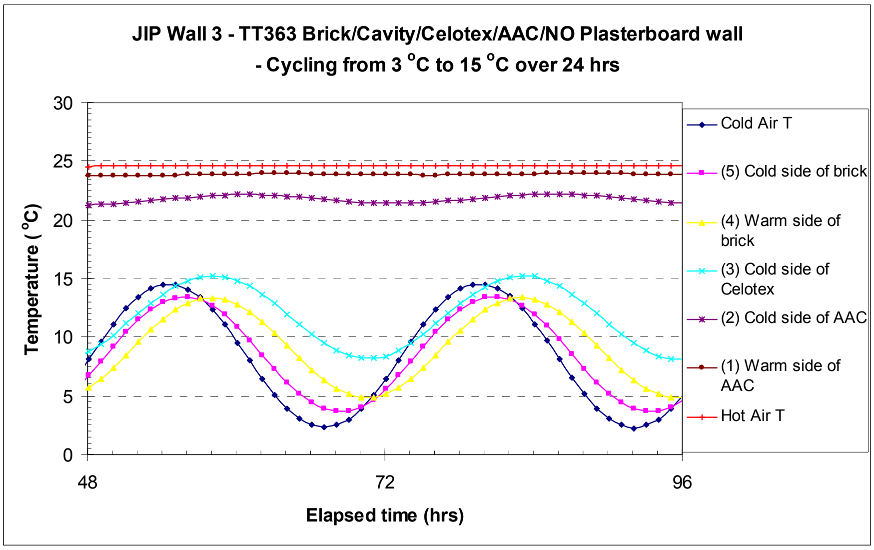
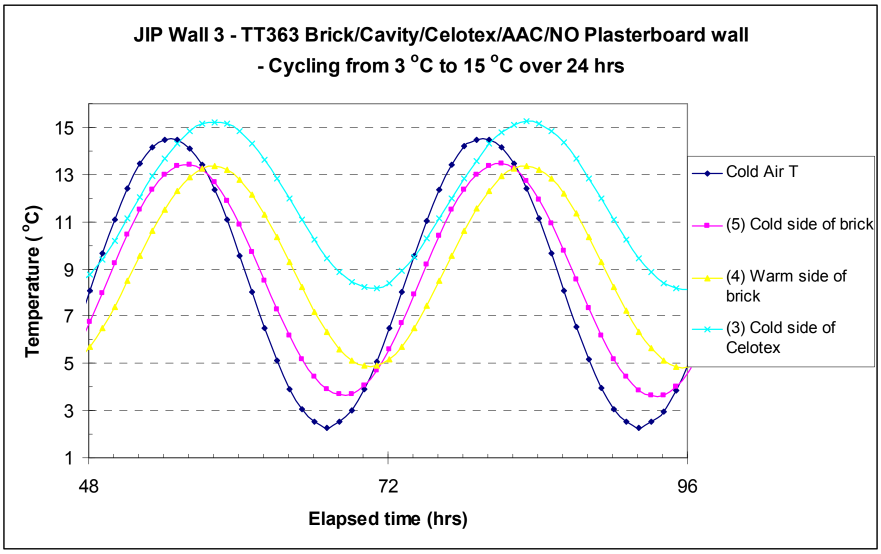


Figure 45 Wall 3 - No Plasterboard -Temperature profiles





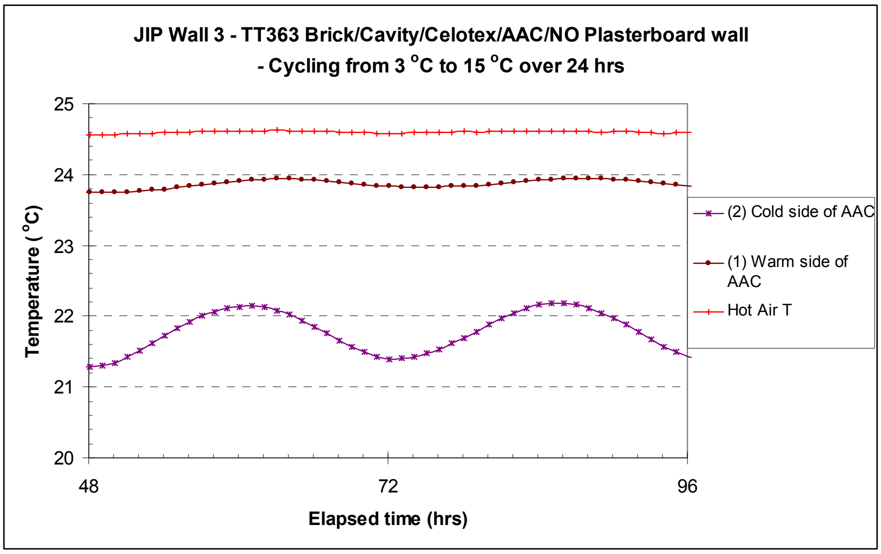


Figure 46 Wall 4 (TT371) - Thermocouple positions for temperature profiles

(1) Hot face of plaster board	(2) Cold face of plaster board	Air cavity	(3) Hot face of EPS	(4) Warm face of concrete	(5) mid position of concrete	(6) Cold face of concrete	(7) Cold face of EPS	(8) Cold face of tiles

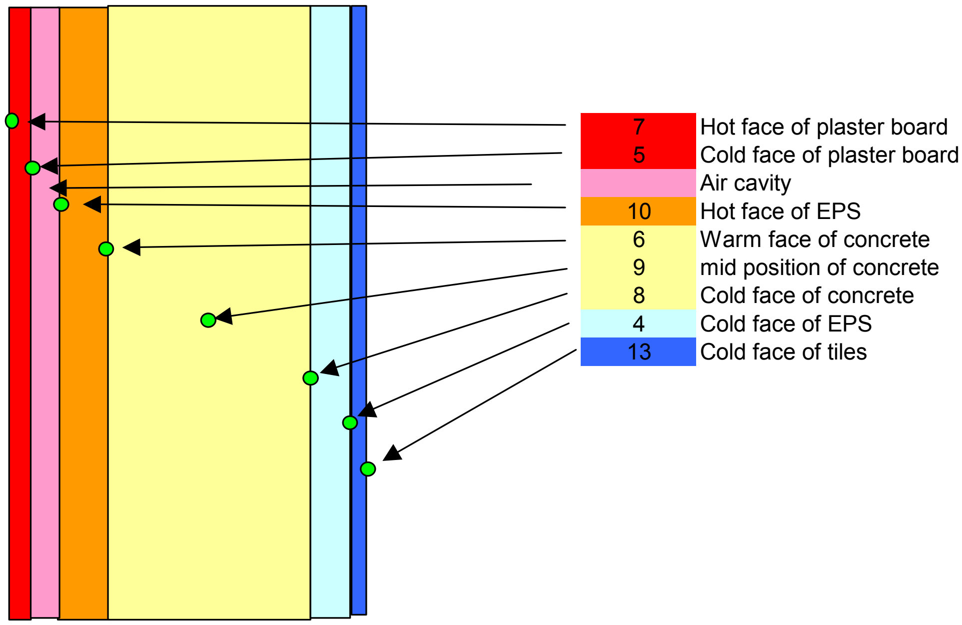
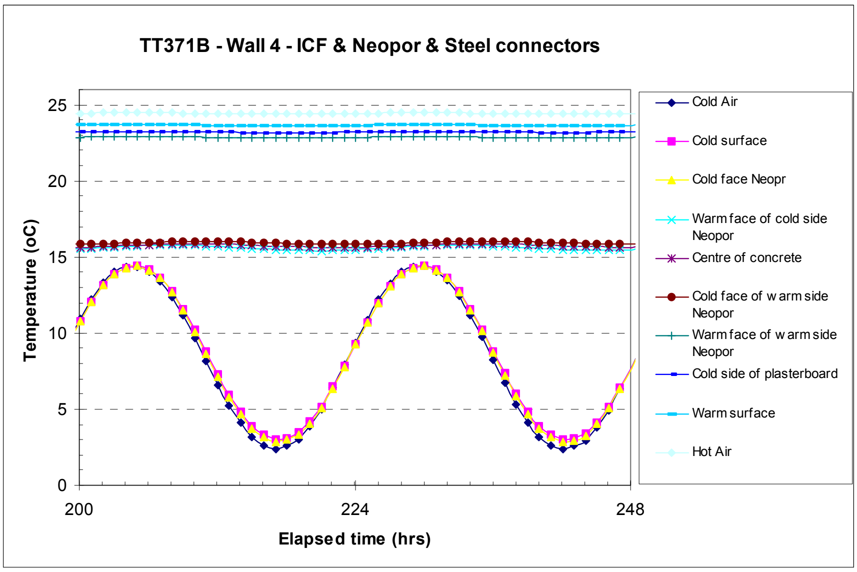
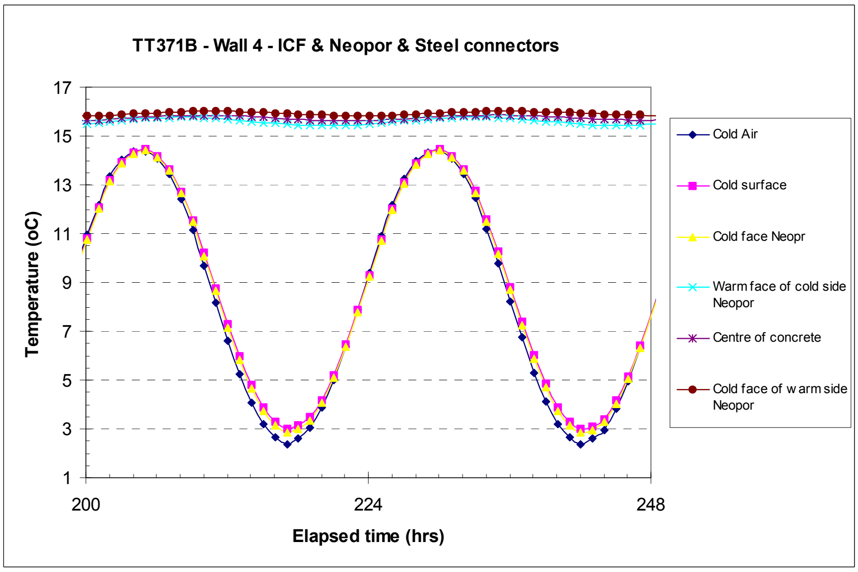


Figure 47 Wall 4 (TT371) Temperature profiles





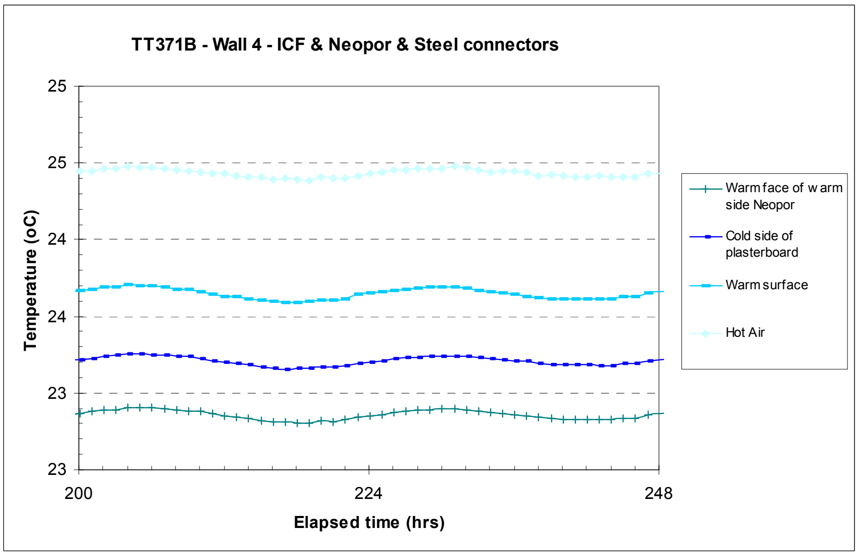


Figure 48 Wall 6 (TT370) - Thermocouple positions

(1) Hot face of plaster board	(2) Cold face of plaster board	Air cavity	(3) Hot face of EPS	(4) Warm face of concrete	(5) mid position of concrete	(6) Cold face of concrete	(7) Cold face of EPS	(8) Cold face of tiles

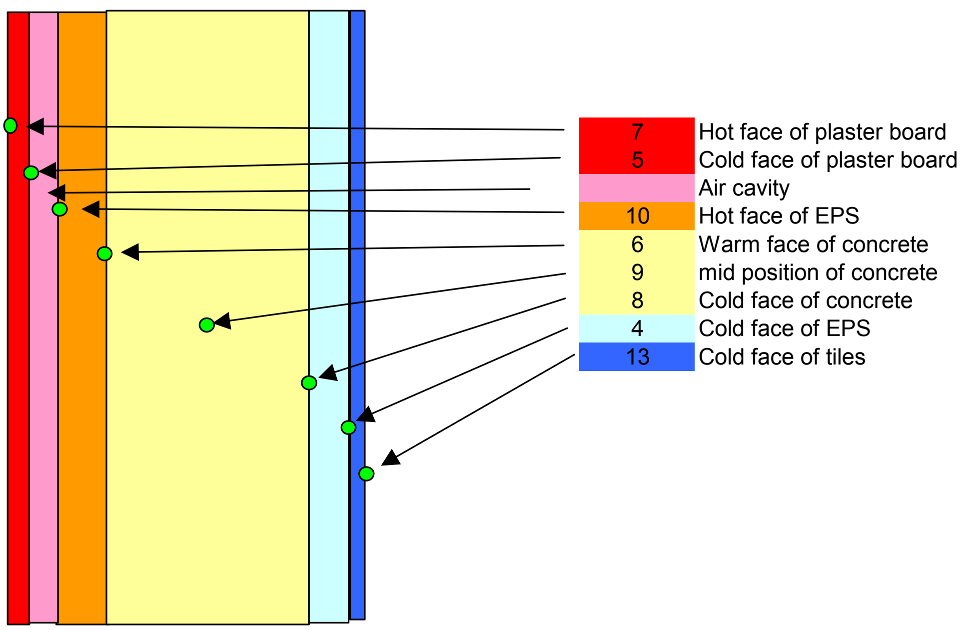
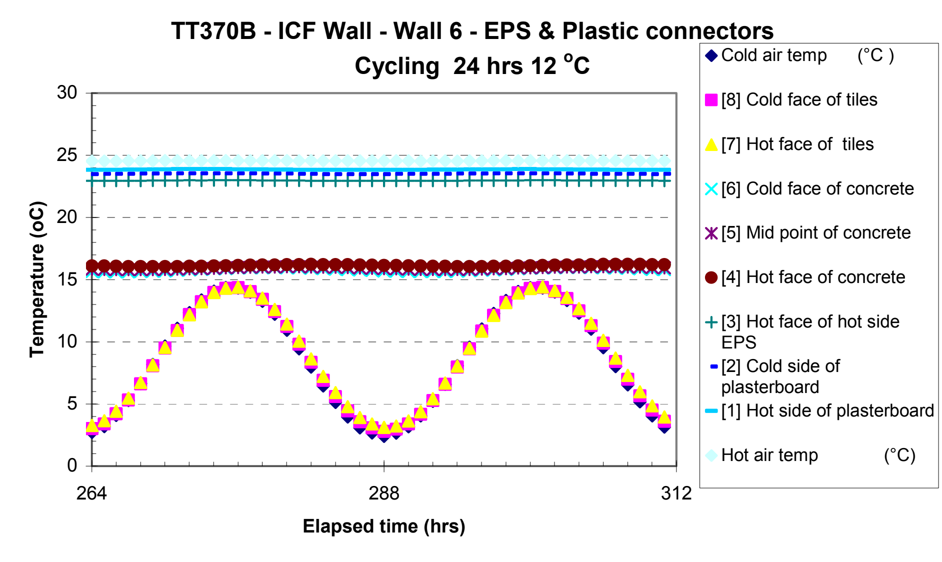
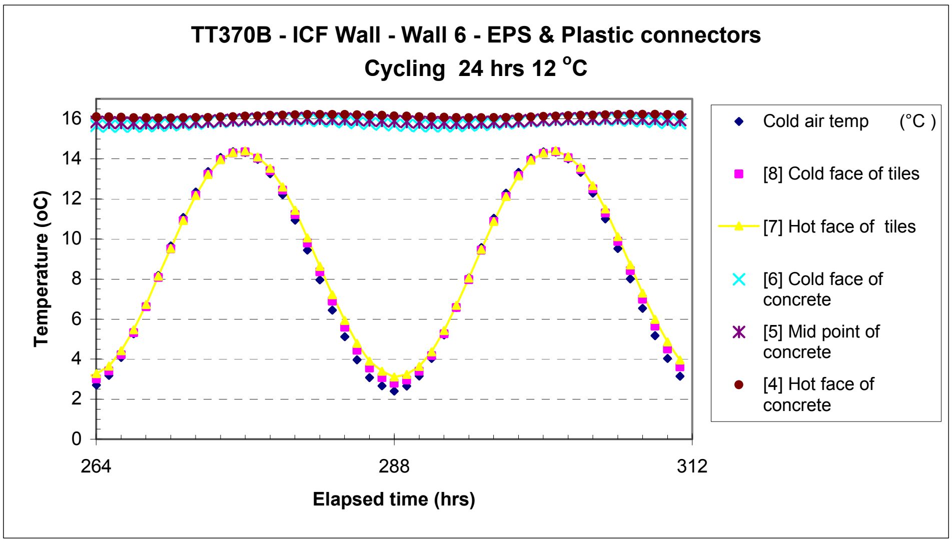


Figure 49 Wall 6 (TT370) - Temperature profiles





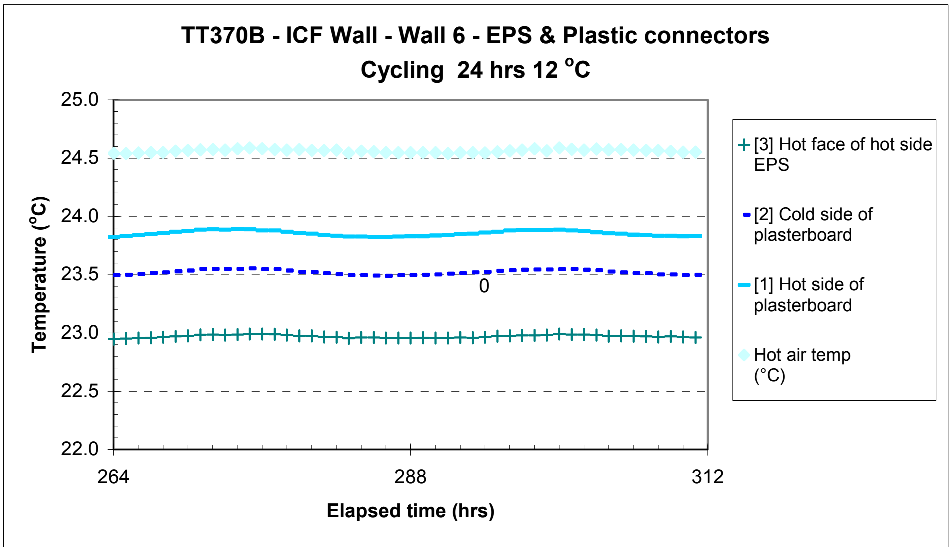


Figure 50 Wall 7 (TT368) - Thermocouple positions

[1] Hot surface of PB	[2] Cold surface of PB	[3] Hot surface of AAC	[4] Hot surface of Celotex	[5] Cold surface of Celotex	[6] Cold surface of tiles

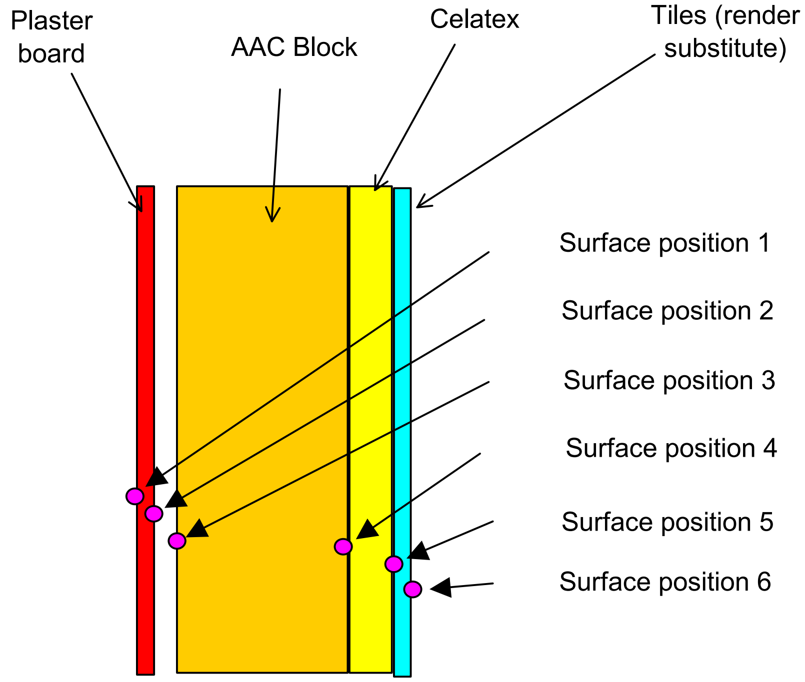
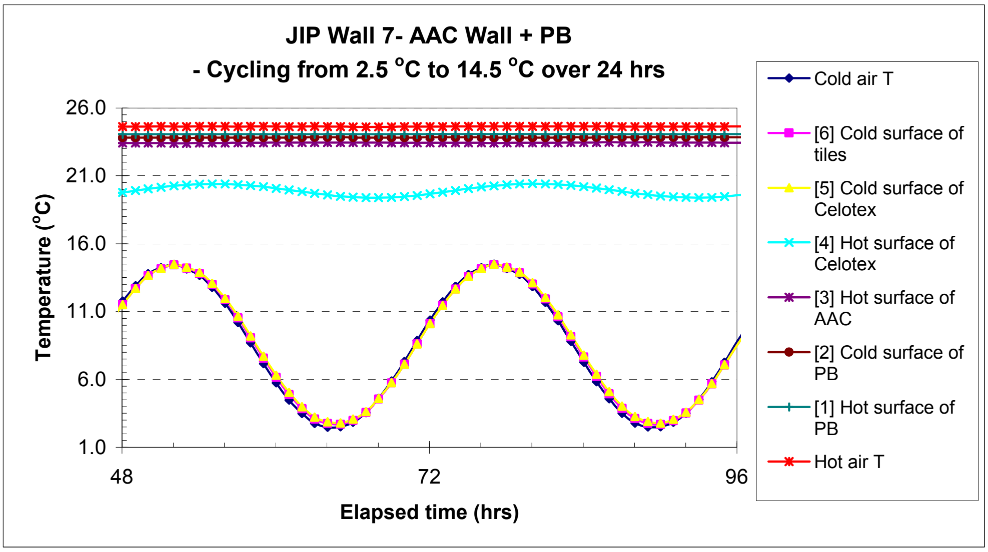
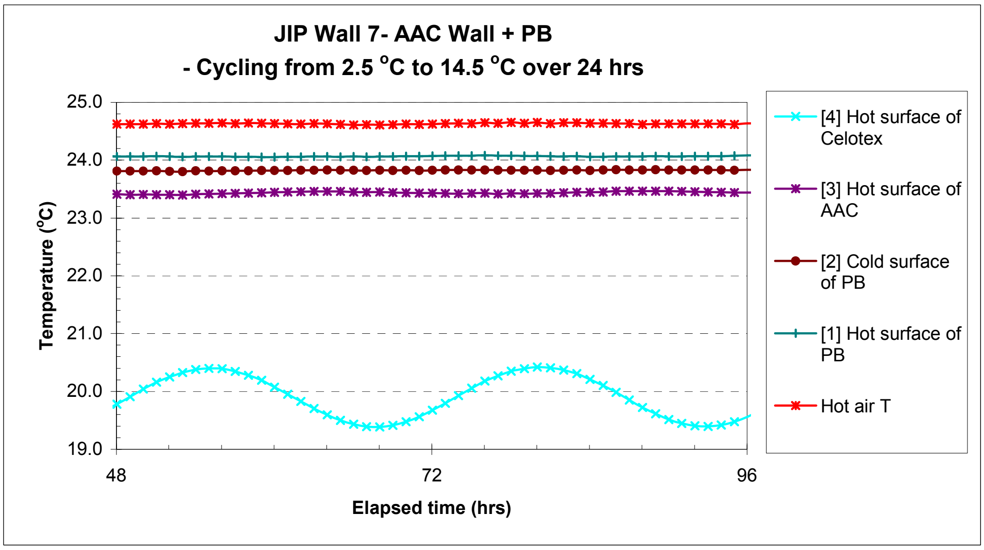


Figure 51 Wall 7 (TT368) - Temperature profiles





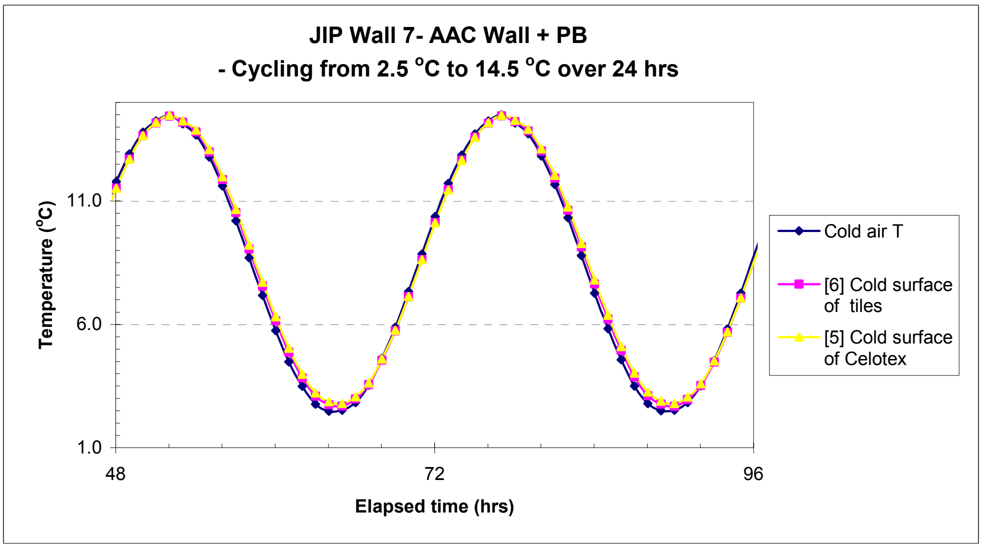


Figure 52 Wall 8 + Plasterboard - Thermocouple positions

(1) Warm surface of PB	(2) Cold surface of PB	(3) Warm surface of concrete	(4) Cold surface of concrete	(5) Cold surface of Celotex	(6) Warm surface of brick	(7) Cold surface of brick

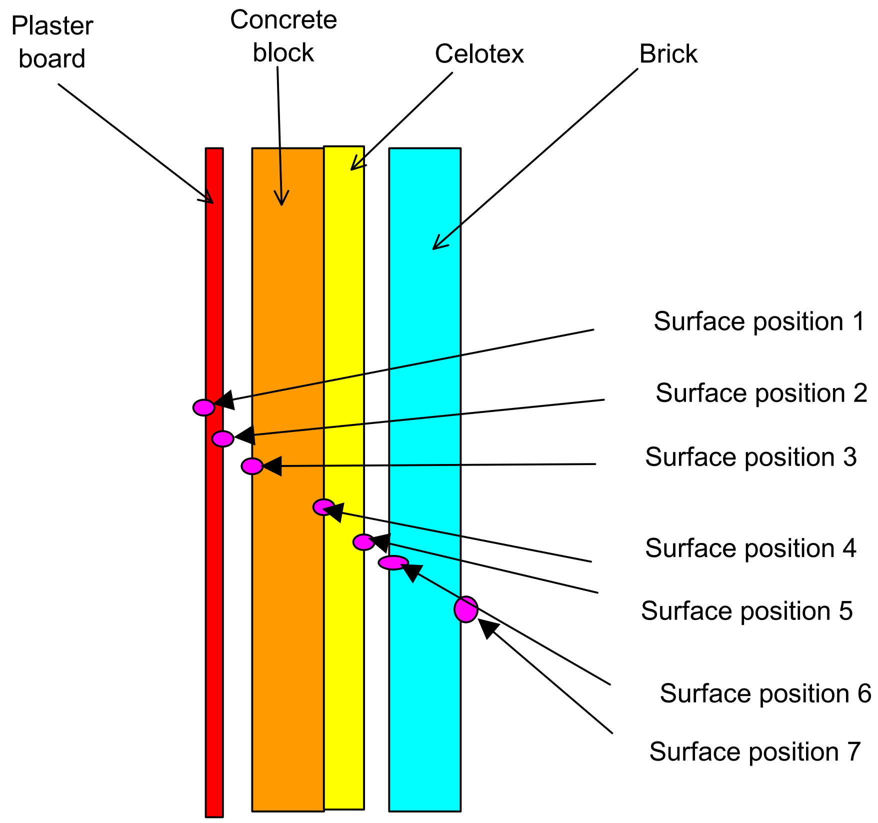
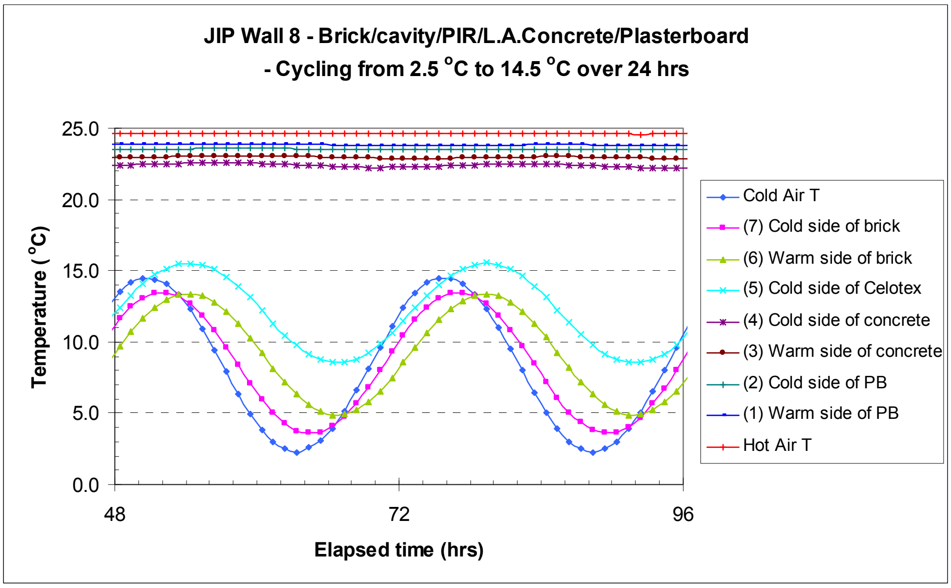
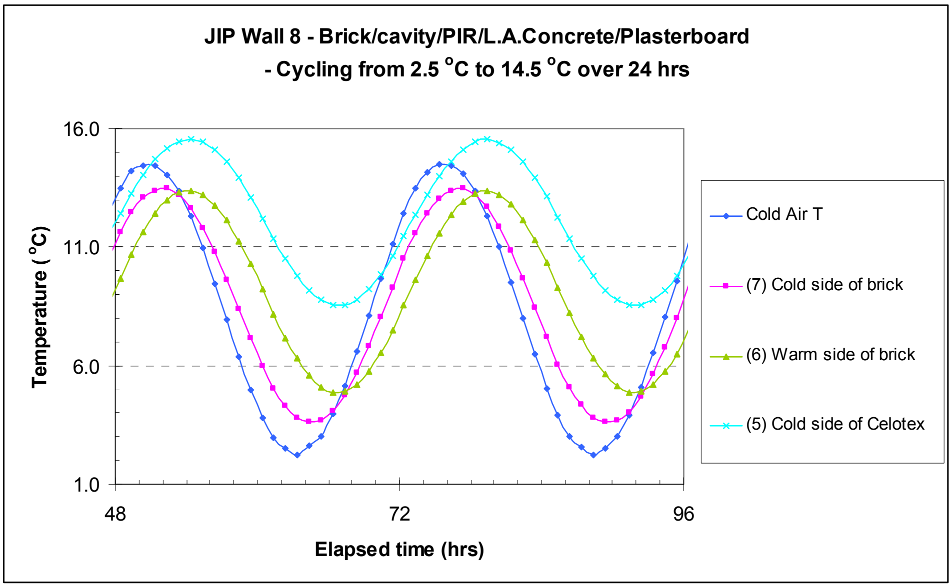


Figure 53 Wall 8 + Plasterboard - Measured temperature profiles





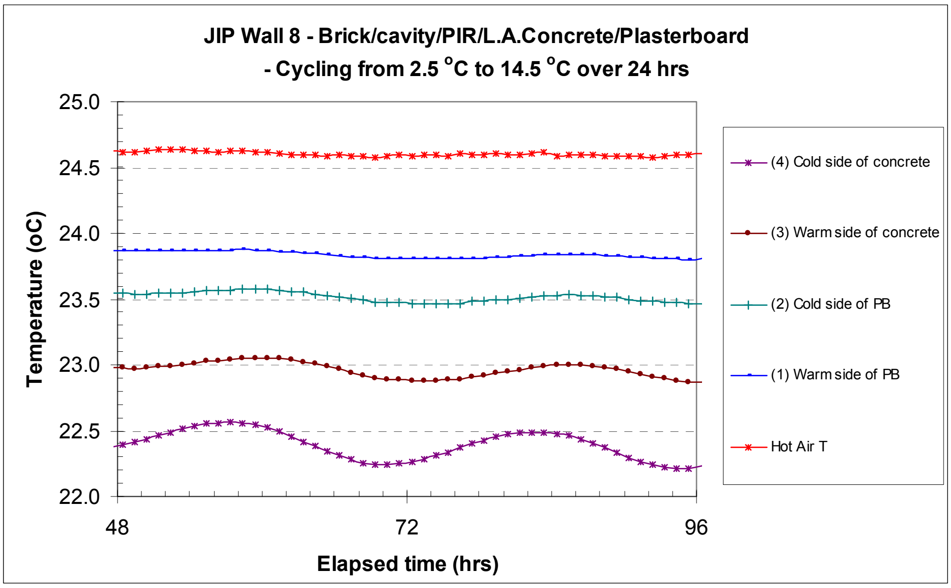


Figure 54 Wall 8 (TT368) - Thermocouple positions

(1) Warm side of concrete	(2) Cold side of concrete	(3) Cold side of Celotex	(4) Warm side of brick	(5) Cold side of brick

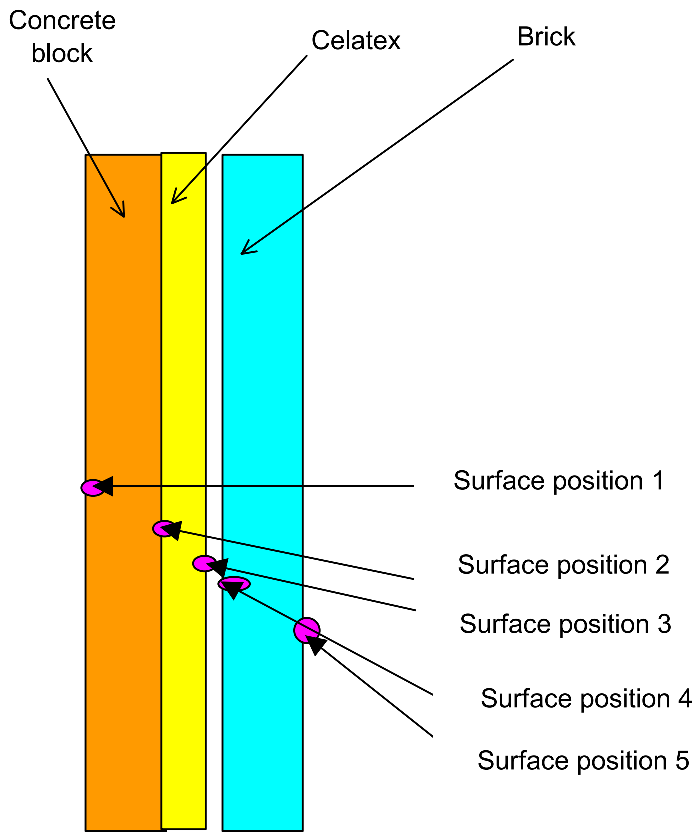
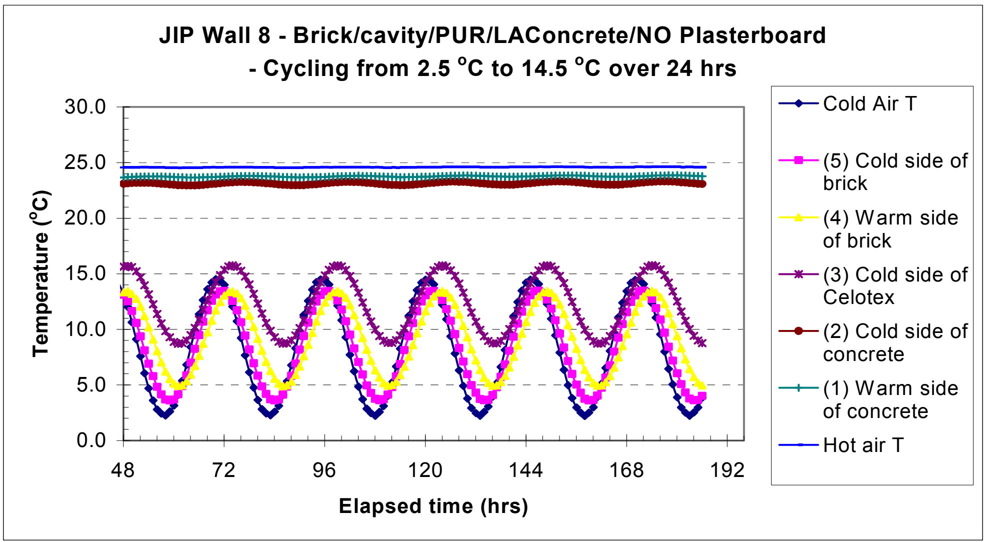
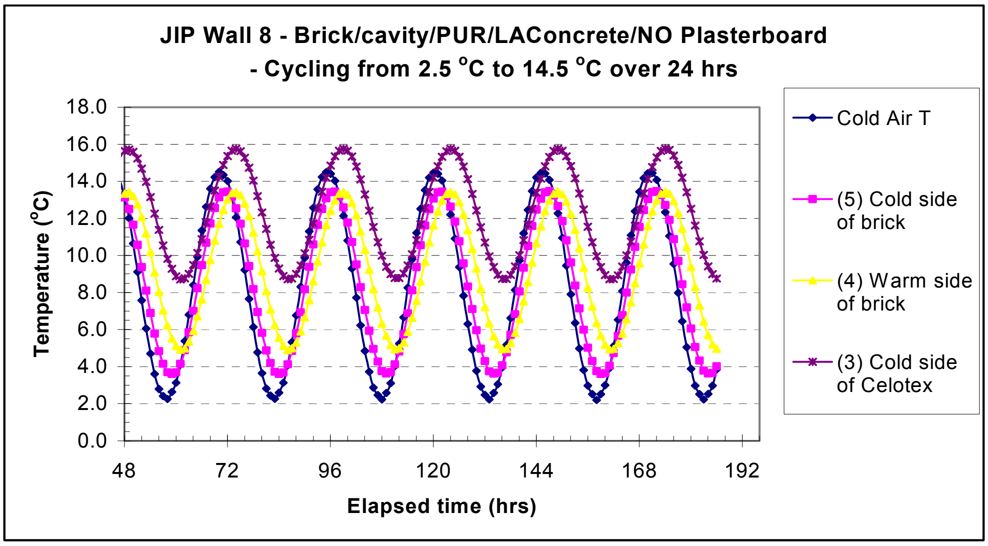
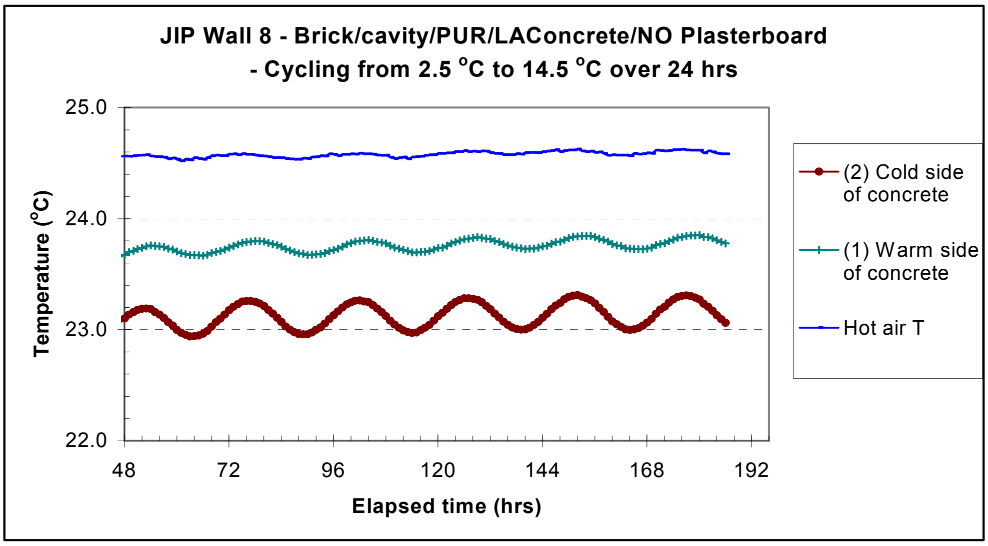


Figure 55 Wall 8 (TT368) – No plasterboard - Temperature profiles







7 RESULTS OF THE THERMAL PERFORMANCE CALCULATIONS

7.1 Overview of modelling methodology

The thermal performance of the walls described in Section 4.3 were modelled by Dr Chris Sanders of Glasgow Caledonian University. These models have not attempted to replicate the NPL measured results exactly, but have been used to examine the differences in performance between the different wall types given temperature inputs similar to those used during the measurements.

Each wall was modelled with the non-steady state, three-dimensional thermal analysis software, VOLTRA, which is one of the Physibel suite of programmes. In most cases the walls were modelled as one metre square sections consisting of a series of parallel material layers, each with a specified, thickness, thermal conductivity, density and specific heat; heat flow was therefore assumed to be one dimensional. The model of the timber framed wall, wall 2, included representative timber studs and battens supporting the external timber cladding, which caused multidimensional heat flow. This model was larger, 1.288 metres x 1.288 metres to accommodate these features.

Standard internal and external heat transfer coefficients, 7.7 W/m^2K and 25 W/m^2K respectively, were used.

7.2 Thermal performance parameters modelled.

For each wall the following thermal properties were modelled.

i) *Steady state U-value*
The model was run with constant inside and outside temperatures of 22°C and 9°C to give a constant heat flow: Q_0 Watts. The U-value of the wall is then calculated from $U = Q_0 / A \cdot \Delta T$ W/m^2K, where ΔT is the imposed temperature difference in °C and A is the area of the model in m^2

ii) *Time constant to a step change in temperature*
The model was run with constant internal and external temperatures of 22°C and then the external temperature dropped instantaneously to 9°C. The heat flow into the internal surface, Q(t) then rises to the steady state value, Q_0, as shown in Figure 56. Then if we assume that the heat flow into wall is responding to the step change as:

$$Q(t) = Q_0 - Q_0 e^{-T/\tau}$$

Where T is the time in hours from the change and τ is the time constant in hours.

Plotting $\log_e(Q_0 - Q)$ against T will give a straight line with slope $-1/\tau$, as shown in Figure 57, which gives a time constant for the timber framed wall as 1/0.143 = 7.0 hours.

iii) *Response to sinusoidal change in external temperature*
In this case, replicating the NPL test, the internal temperature is kept constant at 22°C and the external temperature is fluctuated sinusoidally, with a mean of 9°C, an amplitude of ±6 °C and a period of 24 hours, as shown in Figure 58.

Figure 56 Response of timber framed wall to step change in external temperature

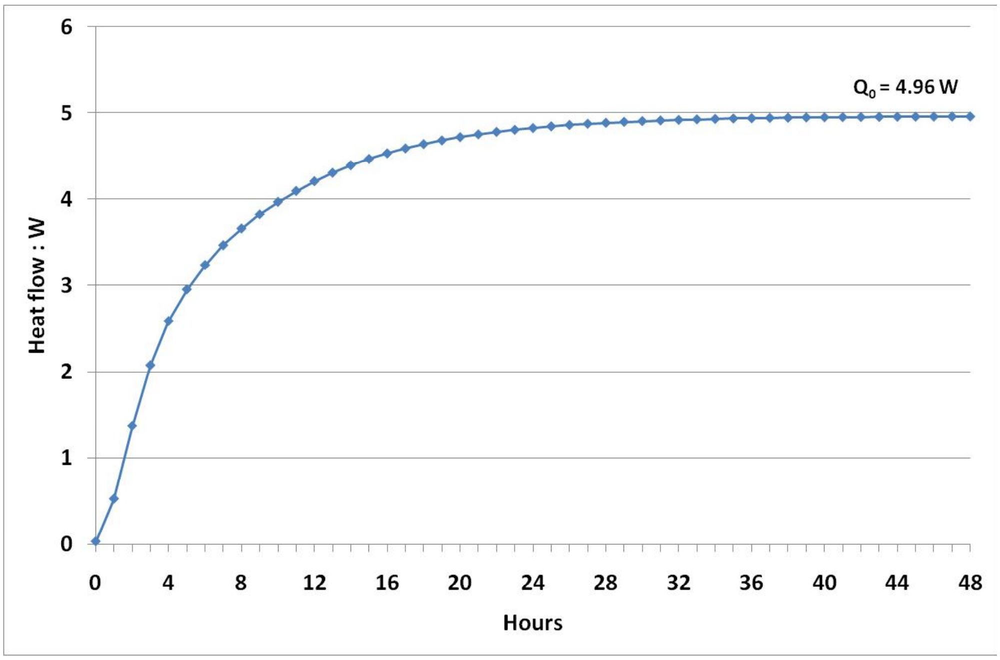


Figure 57 Plot of log(Qo-Q(t)) against time for the timber framed wall.

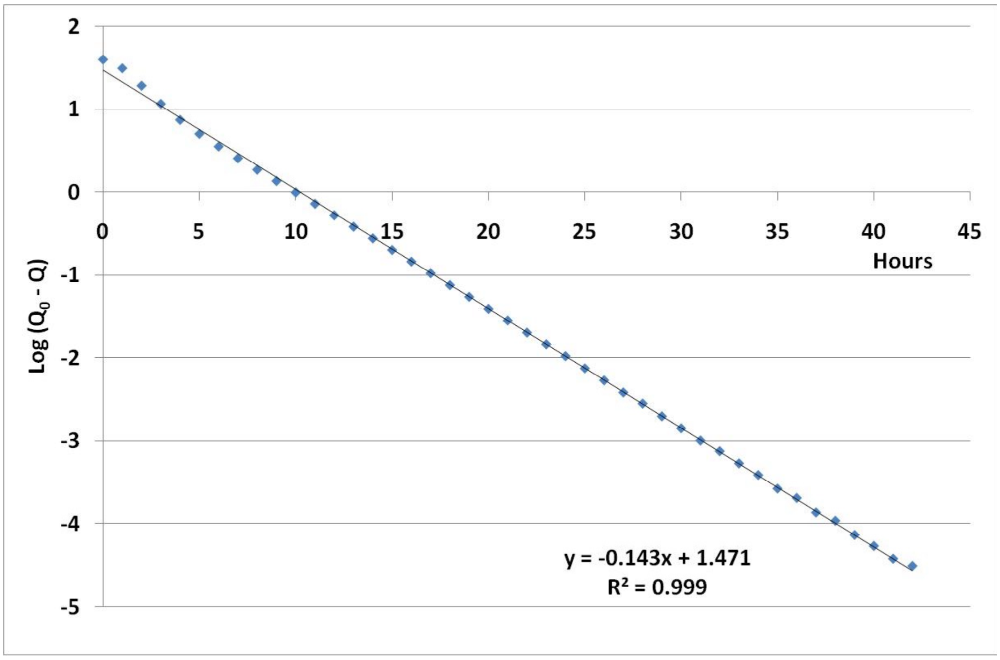
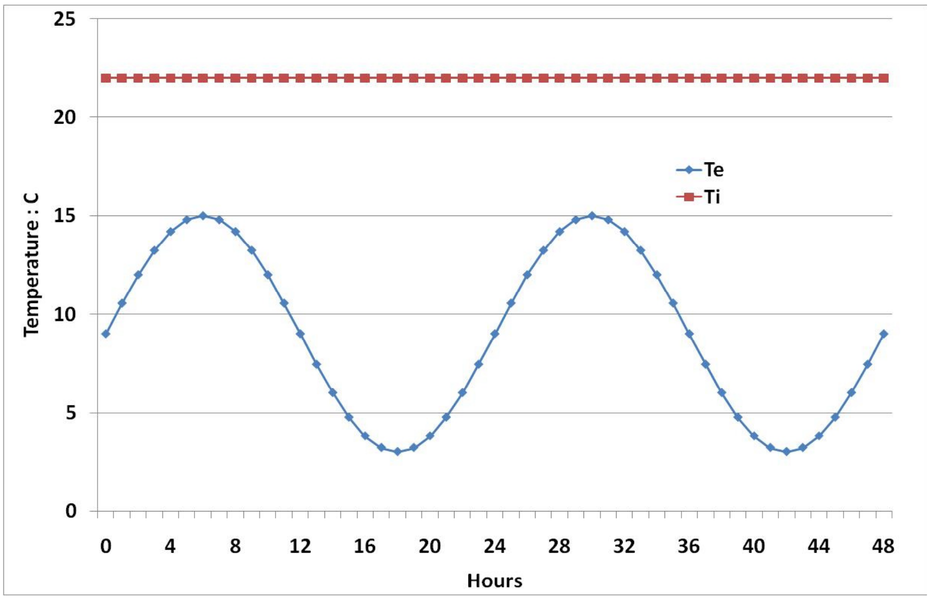


Figure 58 Plot of constant internal and sinusoidal external temperatures



The outputs from these simulations have been used to carry out two sorts of analysis:

a) plotting the hourly values of heat flow into the internal surface of the wall and the temperature difference across the wall against time, as shown in Figure 59, gives the number of hours that the heat flow lags behind the temperature difference and also the amplitude of the daily cycle of heat flows into the wall.

b) An instantaneous U-value can be calculated by dividing the heat flow by the temperature difference as shown in Figure 60; this fluctuates widely because the heat flow is out of phase with the temperature difference. However a cumulative average (rolling average) of the U-values settles down to a reasonably precise value after 10 days, as shown in Figure 61. This technique is used in analysing in-situ U-value measurements.

Figure 59 Timber wall - Temperature differences and heat flows - cycling from 3°C to 15°C

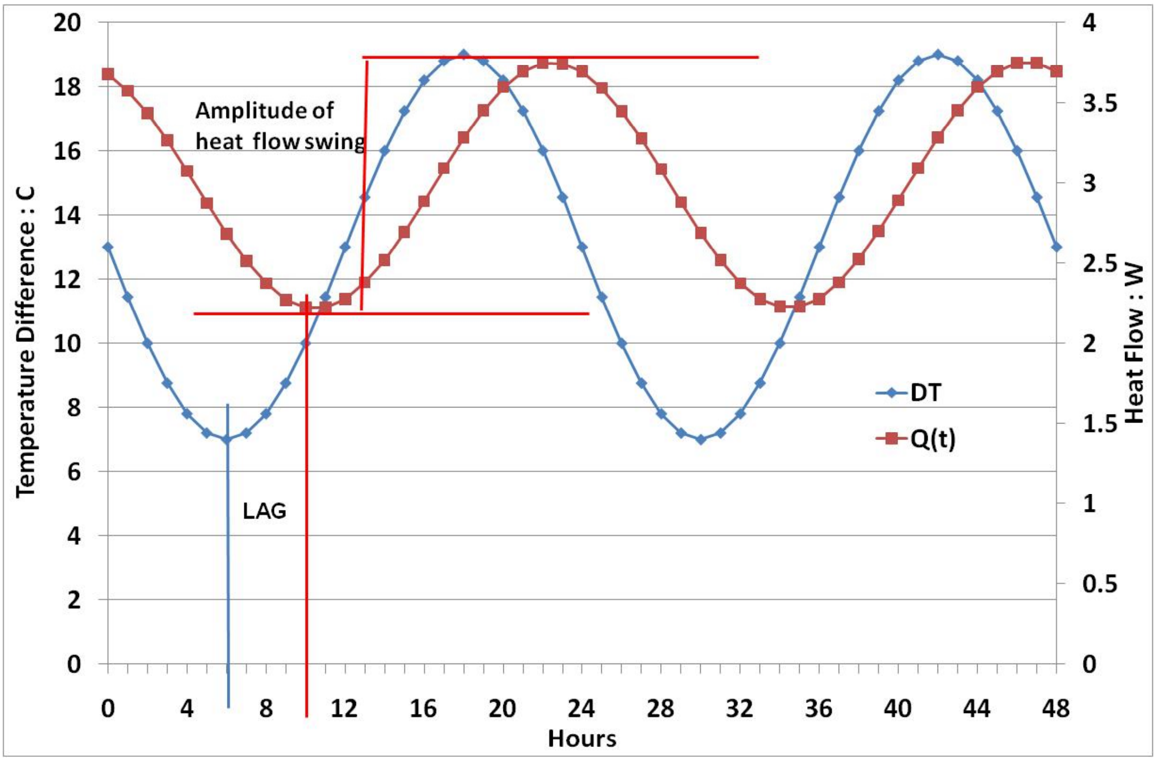


Figure 60 Instantaneous U-value for timber framed wall

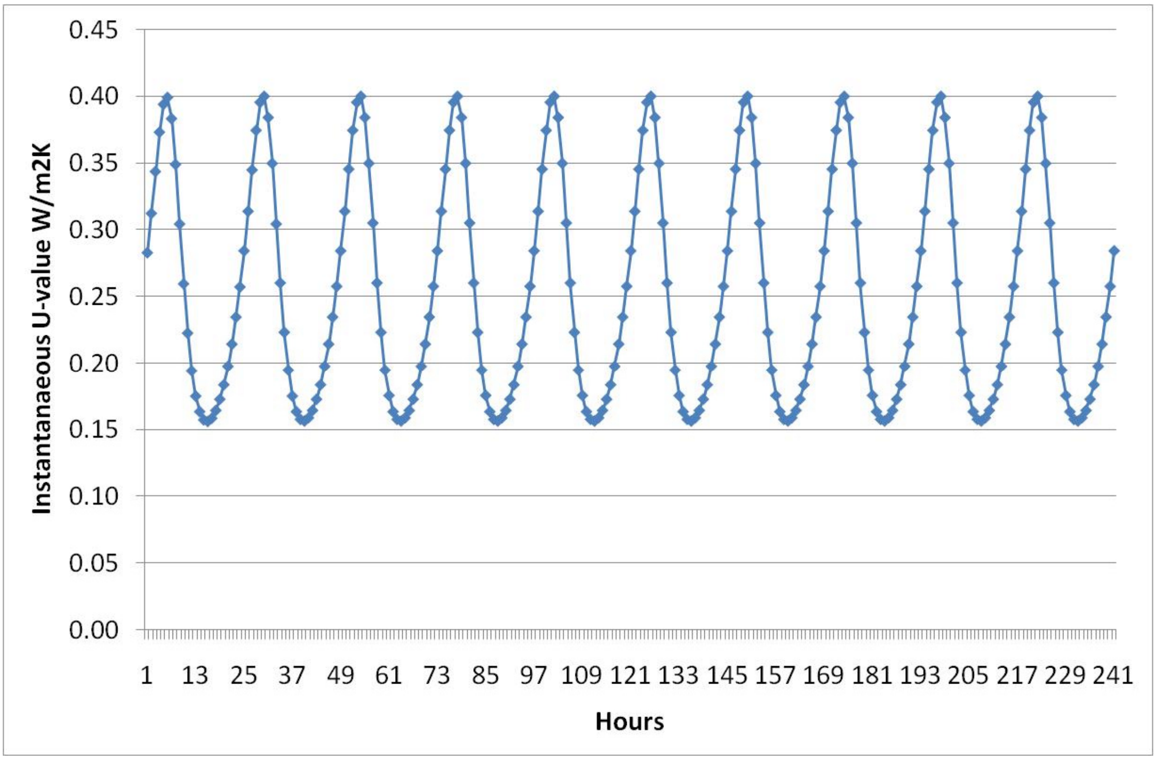
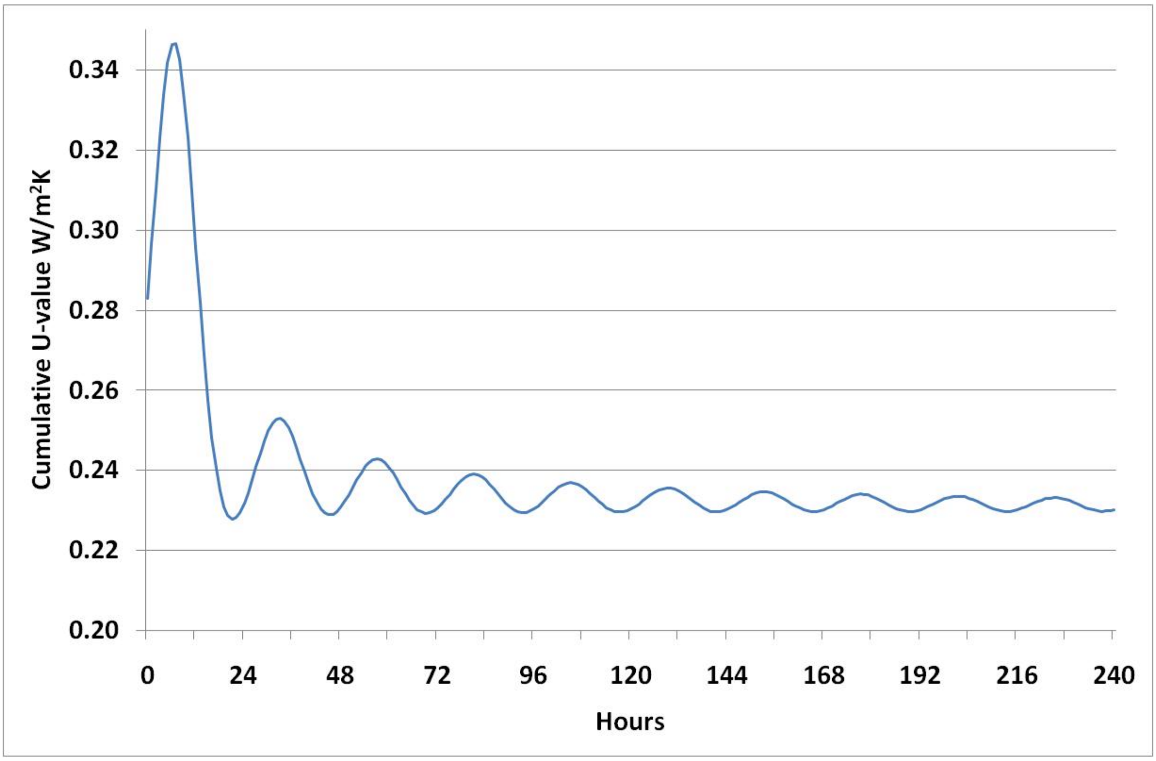


Figure 61 Rolling average U-value for timber framed wall



7.3 Details of the heat transfer modelling for each wall

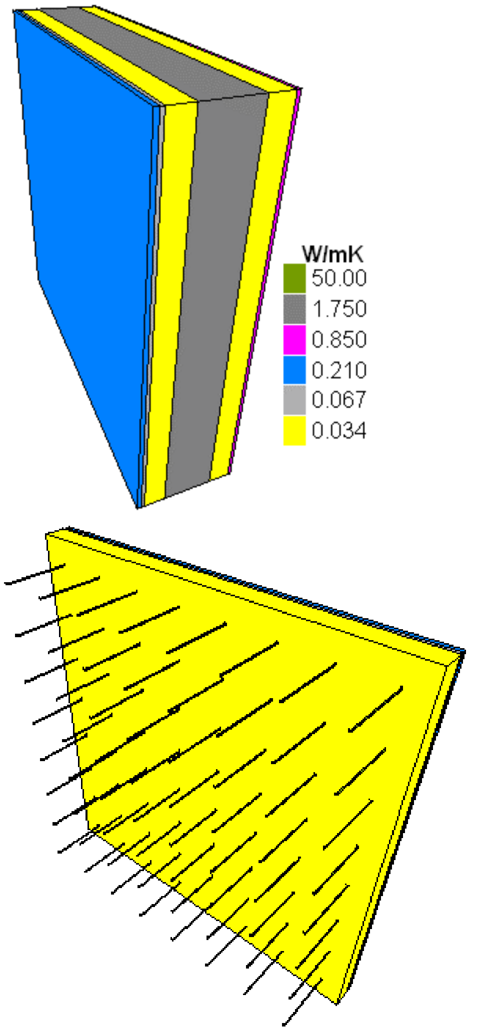
7.3.1 Wall 1 ICF – EPS insulation and steel ties

Table 11 Details of materials in Wall 1

Material	Width mm	Conductivity W/m·K	Density kg/m^3	Specific Heat J/kg·K
Plasterboard	12.5	0.21	700	1000
Cavity	10	0.067	1.2	1000
EPS	65	0.034	24	1450
Concrete	150	1.75	2400	1000
EPS	65	0.034	24	1450
Render	9	0.85	1900	850
Steel ties	3	50	7800	480

Steel ties - Assumed to be 3 mm dia. at 150mm centres in both directions, penetrating 53 mm into the insulation on both sides.

Figure 62 Wall 1 - Model and boundary conditions



Steel ties

Model area = 1.192 * 1.192 = 1.42m^2

Steady state Ti=22°C, Te = 9°C Q = 4.65 W

U = 0.252 W/m^{2}K

Step change time constant = 98.0 hours

Sinusoid time lag = 2 hours

Heat flow amplitude = 0.16 W

Cumulative U-value = 0.252 W/m^{2}K

Figure 63 Wall 1 - Heat flow with step change of external temperature from 22°C to 9°C

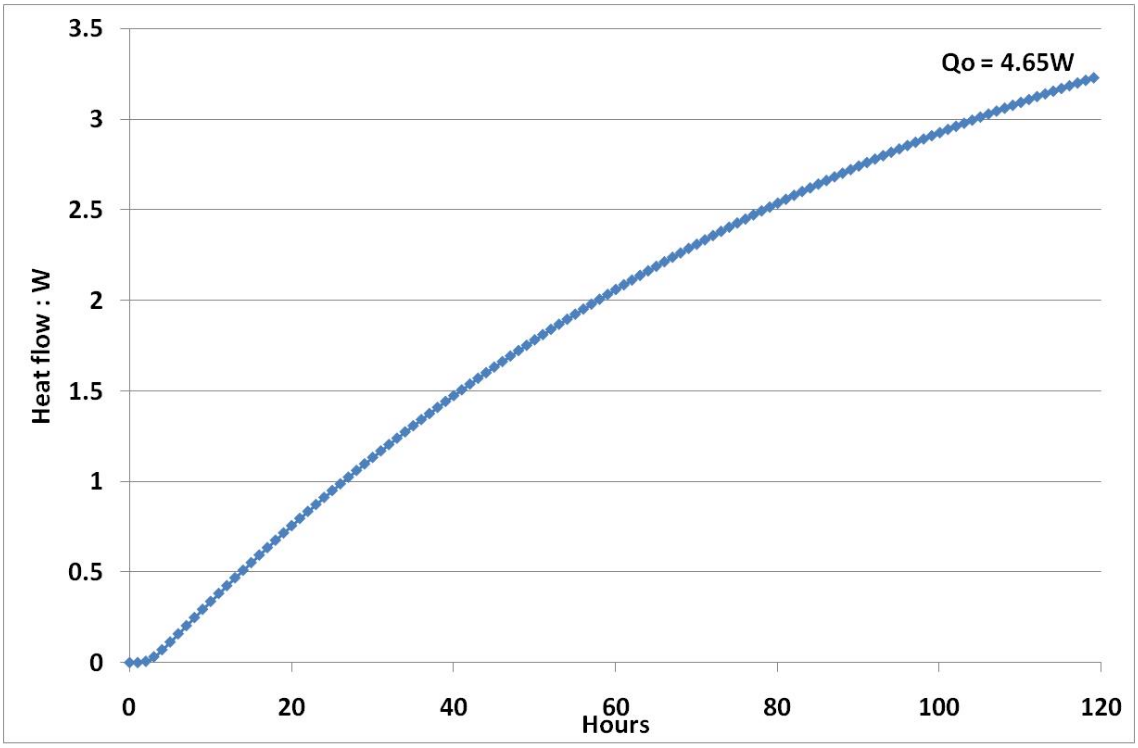


Figure 64 Wall 1 - Plot of log(Qo-Q(t)) against time.

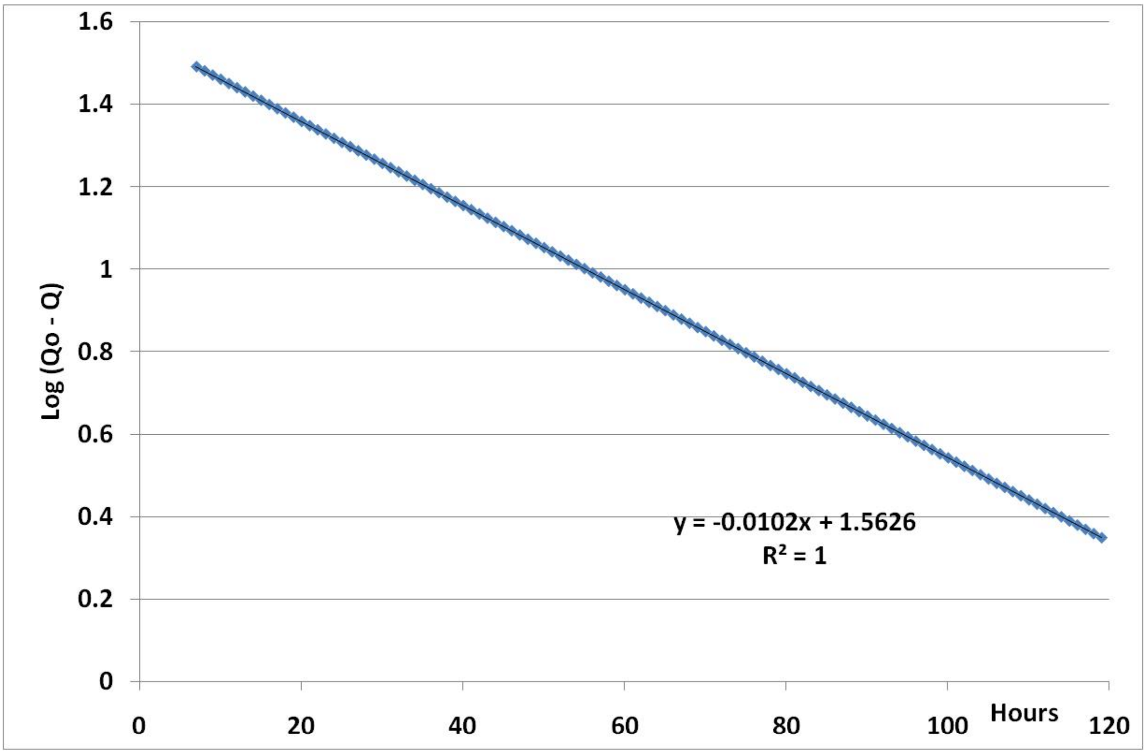


Figure 65 Wall 1 – Heat flow - external sinusoidal temperature, internal temperature constant.

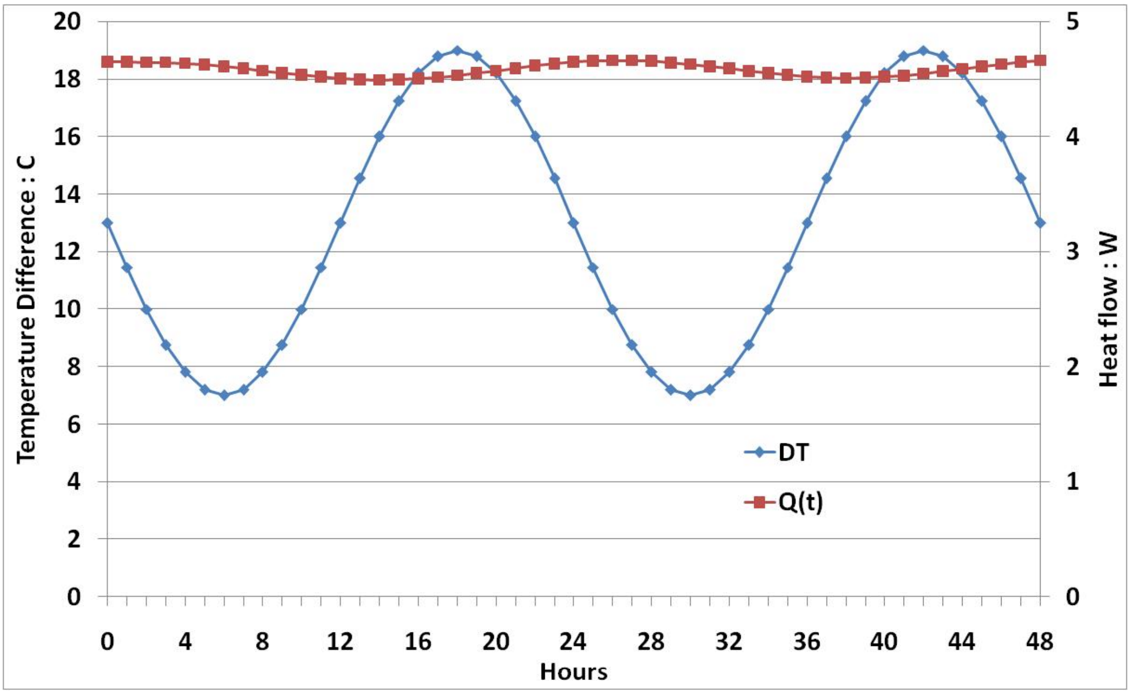
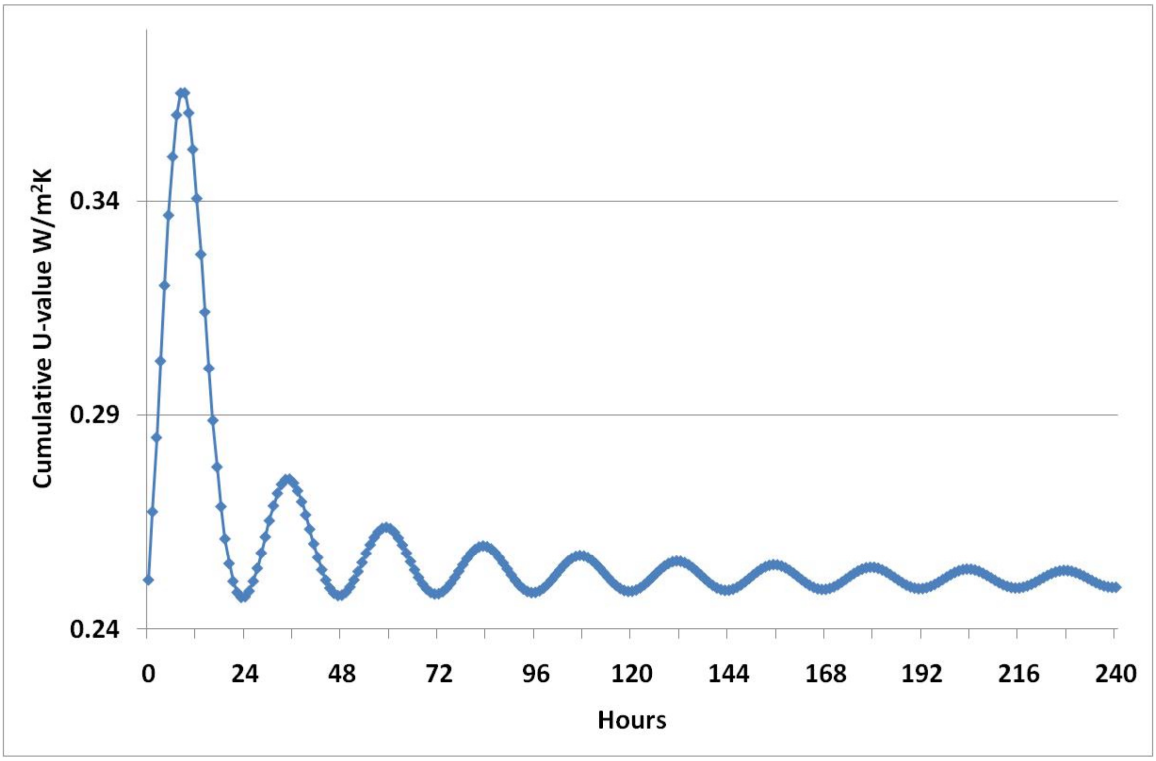


Figure 66 Wall 1 - Rolling average U-value

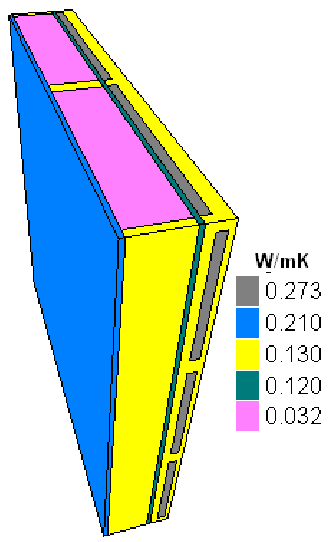


7.3.2 Wall 2 – Timber frame with 140 mm mineral wool insulation

Table 12 Details of materials in Wall 2

Material	Width mm	Conductivity W/m·K	Density kg/m^3	Specific Heat J/kg·K
Plasterboard	12.5	0.21	700	930
Rockwool	140	0.032	40	840
Plywood	12	0.12	600	1880
50mm cavity	50	0.273	1.2	1000
Timber	15	0.13	700	2070

Figure 67 - Wall 2 - Model & boundary conditions



Model area = 1.288 * 1.288 = 1.66m^2

Steady state Ti=22°C, Te = 9°C Q = 4.85 W

U = 0.230 W/m^{2}K

Step change time constant = 7.0 hours

Sinusoid time lag =4 hours

Heat flow amplitude = 1.52 W

Cumulative U-value = 0.230 W/m^{2}K

Figure 68 Wall 2 - heat flow with to step change of external temperature from 22°C to 9°C

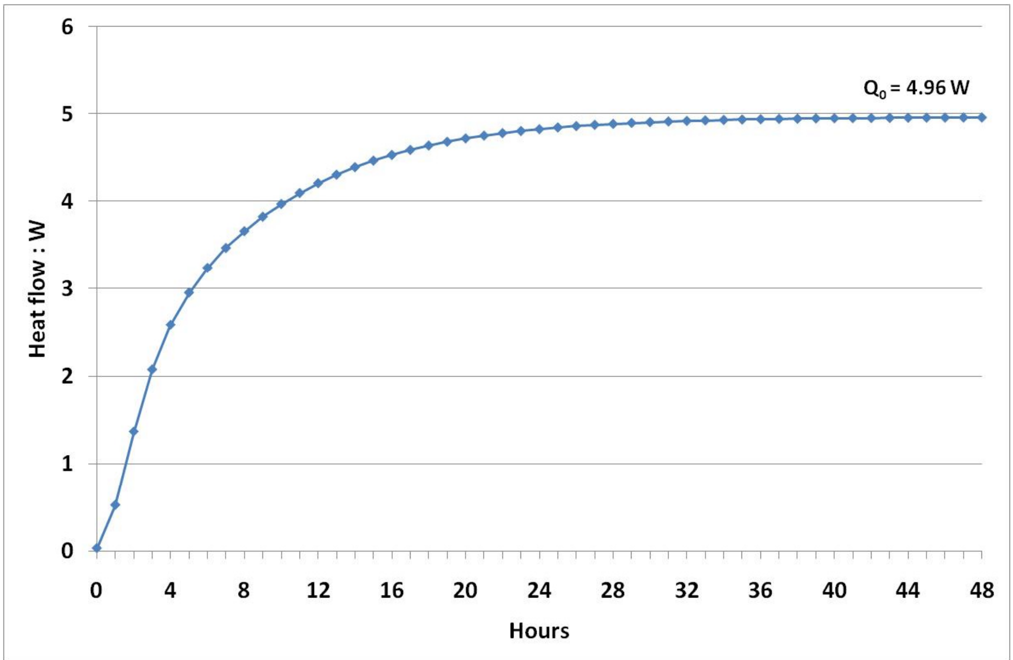


Figure 69 Wall 2 - Plot of log(Qo-Q(t)) against time

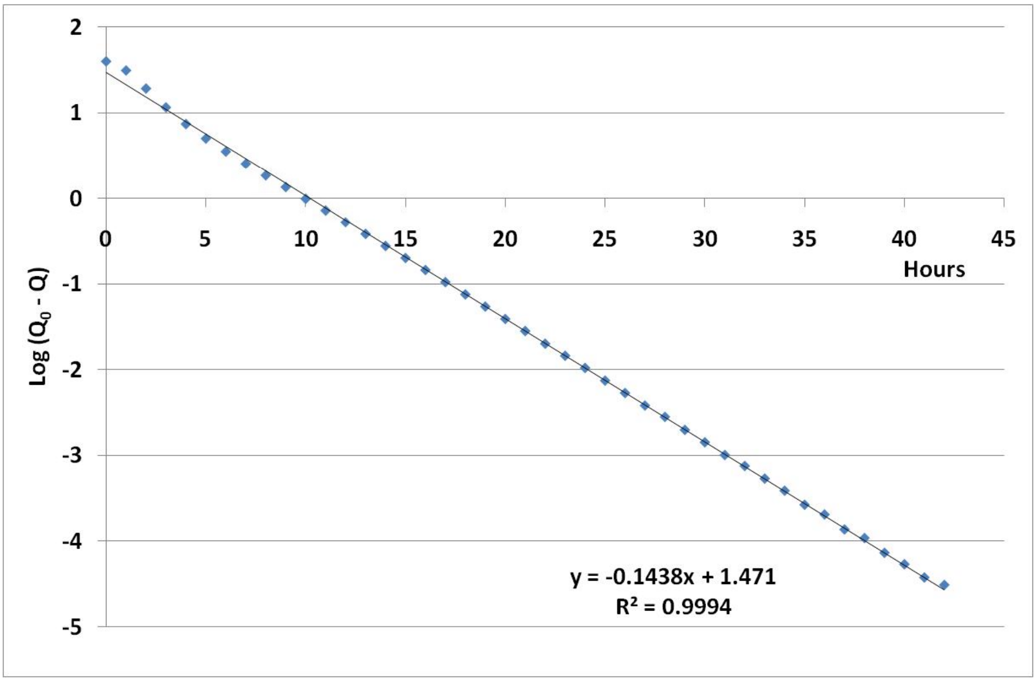


Figure 70 Wall 2 - Heat flow - external sinusoidal temperature, internal temperature constant.

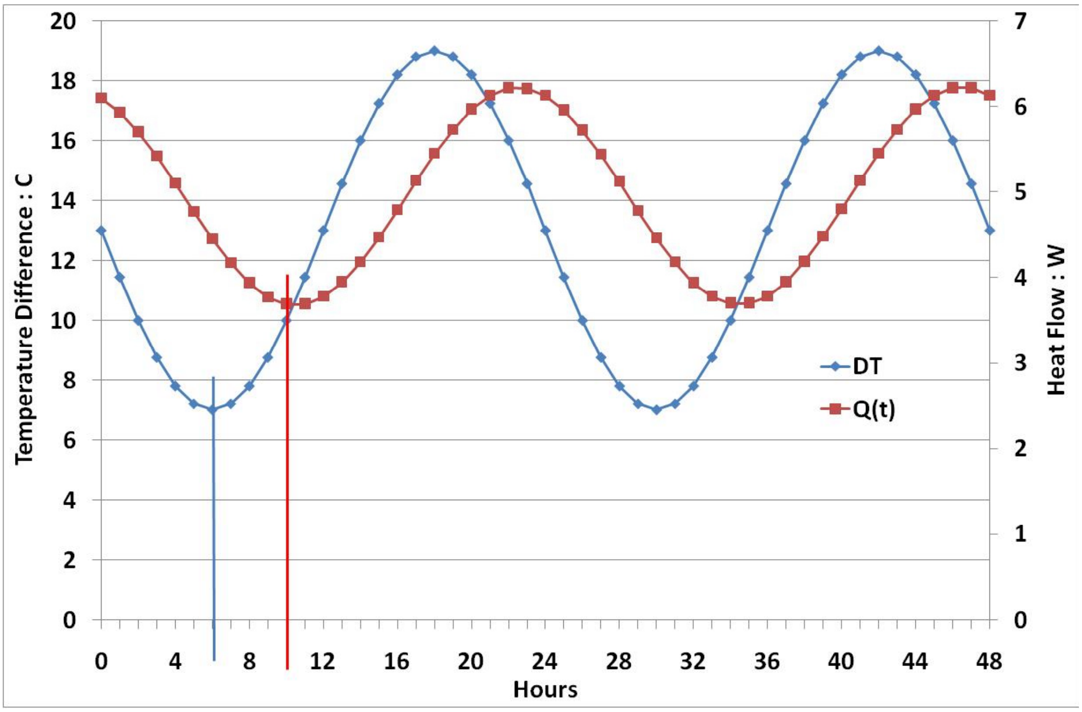
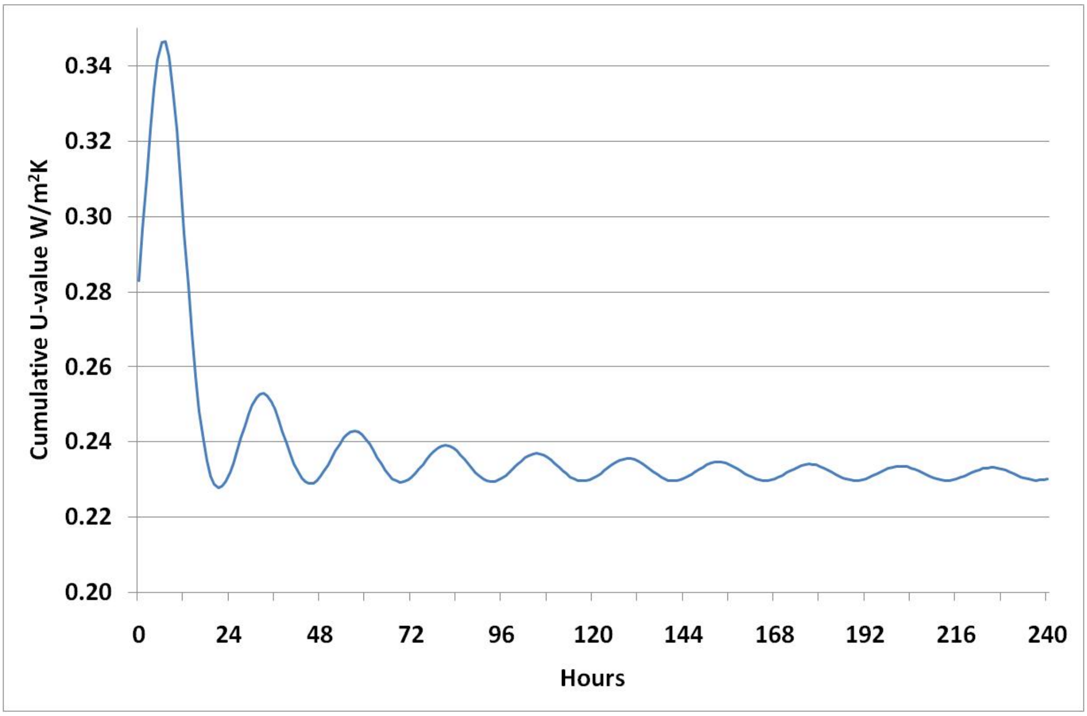


Figure 71 - Wall 2 - Rolling average U-value



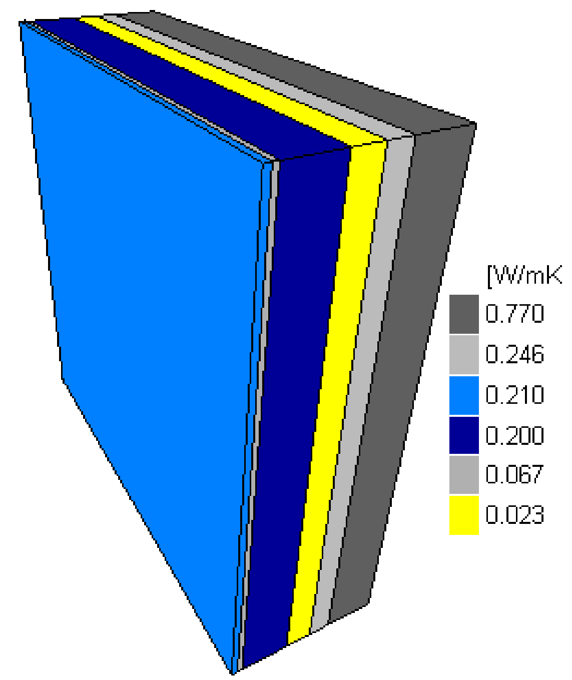
Wall 3 – Brick – PIR – AAC

Table 13 Details of materials in Wall 3

Material	Width mm	Conductivity W/m·K	Density kg/m^3	Specific Heat J/kg·K
Plasterboard	12.5	0.21	700	1000
Cavity	10	0.067	1.2	1000
Block	100	0.15	600	1010
PUR	55	0.023	30	1400
Cavity	45	0.102*	1.2	1000
Brick	102	0.77	1750	1000

[*] The emissivity of the foil faced PIR is assumed to be 0.2

Figure 72 Wall 3 - Model and boundary conditions



Model area = 1.0 * 1.0 = 1.0 m^2

Steady state Ti=22°C, Te = 9°C, Q = 3.242 W

U = 0.249 W/m^2K

Step change time constant = 8.65 hours

Sinusoidal time lag = 10 hours

Heat flow amplitude = 0.82 W

Cumulative U-value = 0.249 W/m^2K

Figure 73 Wall 3 - Heat flow with step change of external temperature from 22°C to 9°C

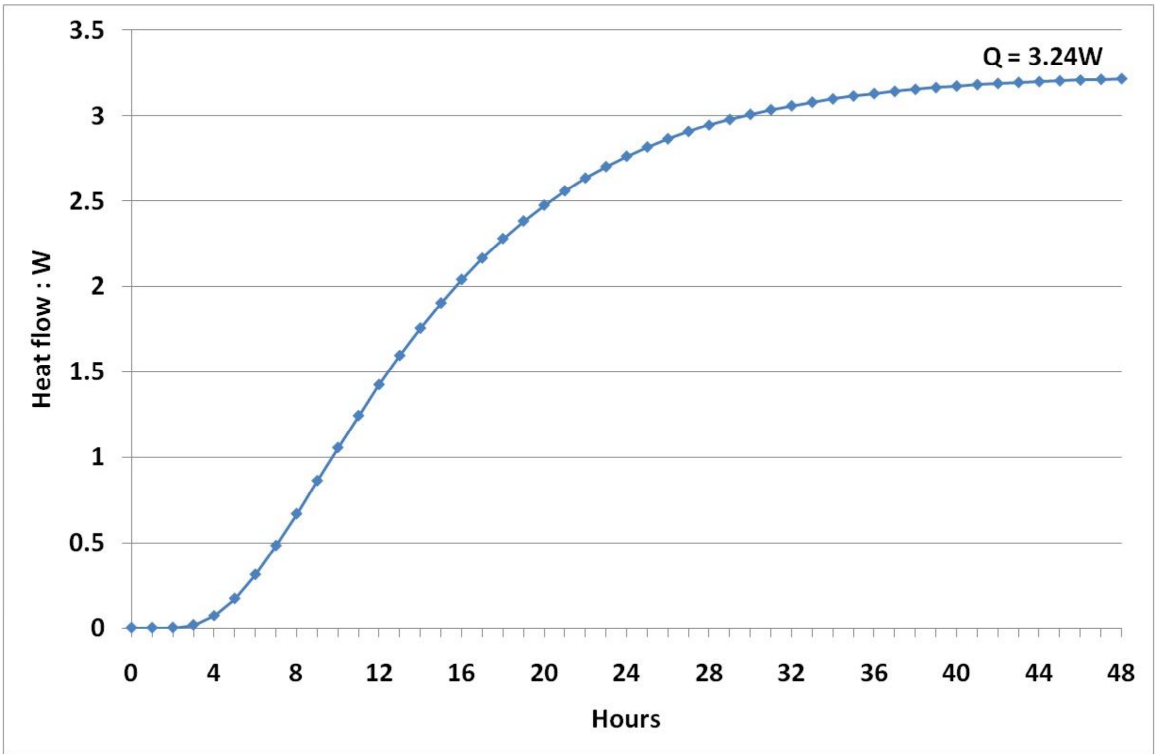


Figure 74 Wall 3 - Plot of log(Qo-Q(t)) against time

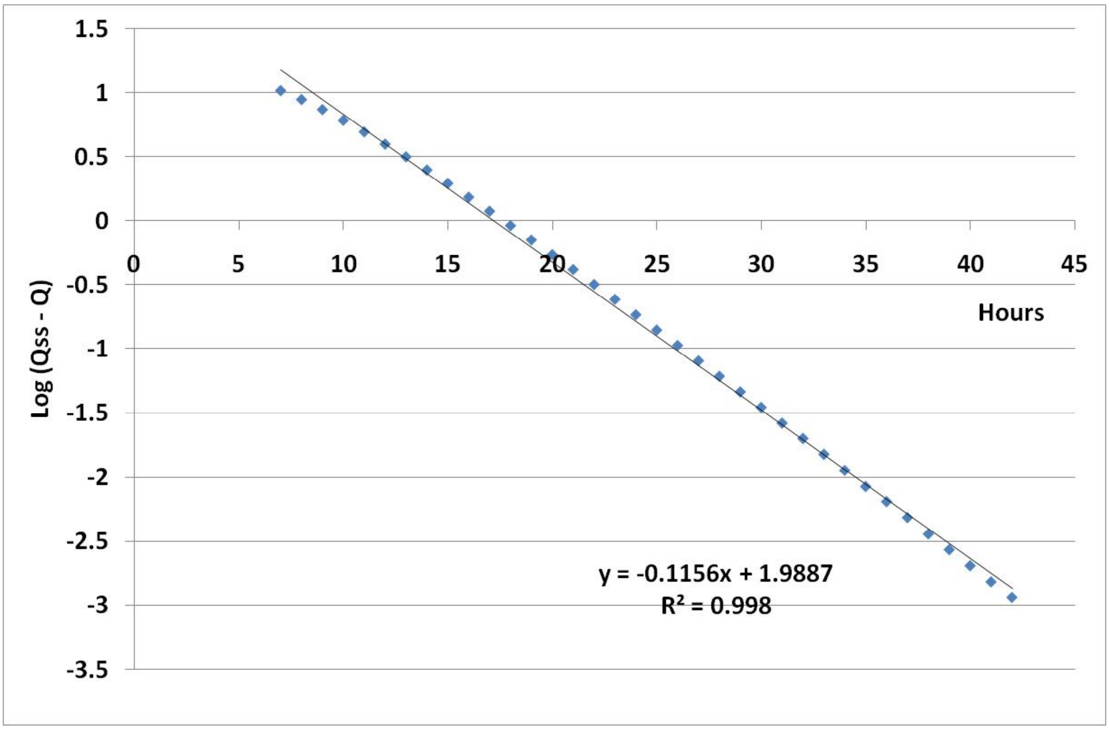


Figure 75 Wall 3 – Heat flow - external sinusoidal temperature, internal temperature constant.

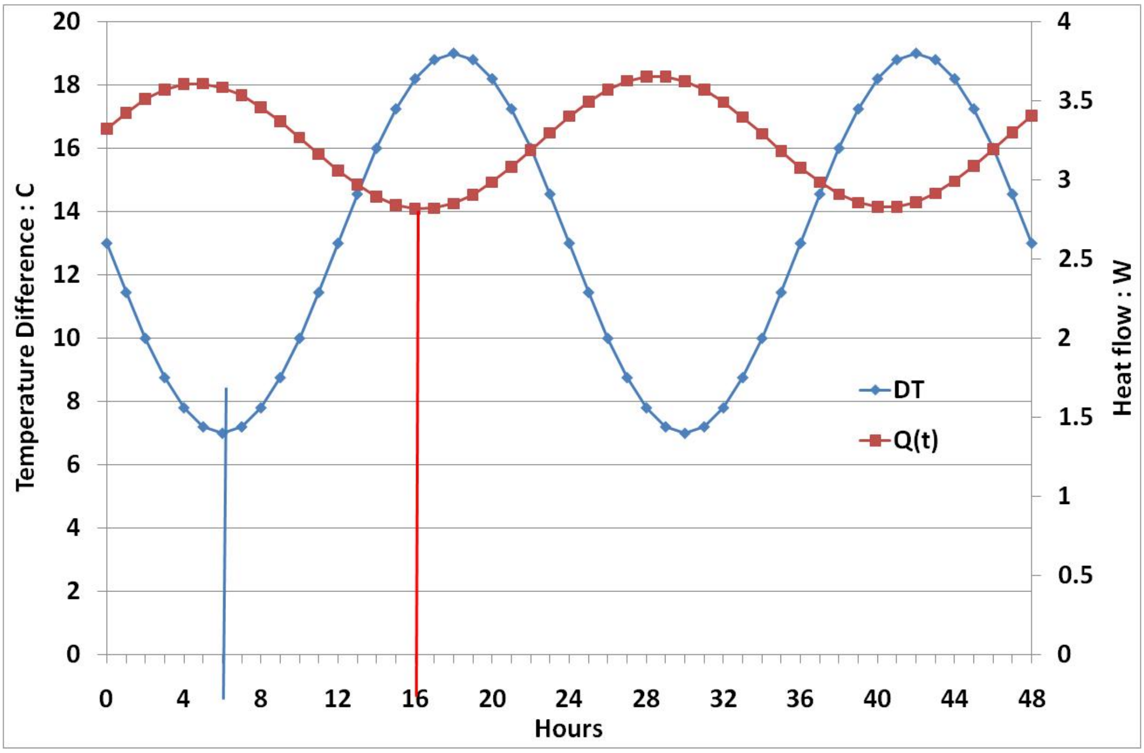
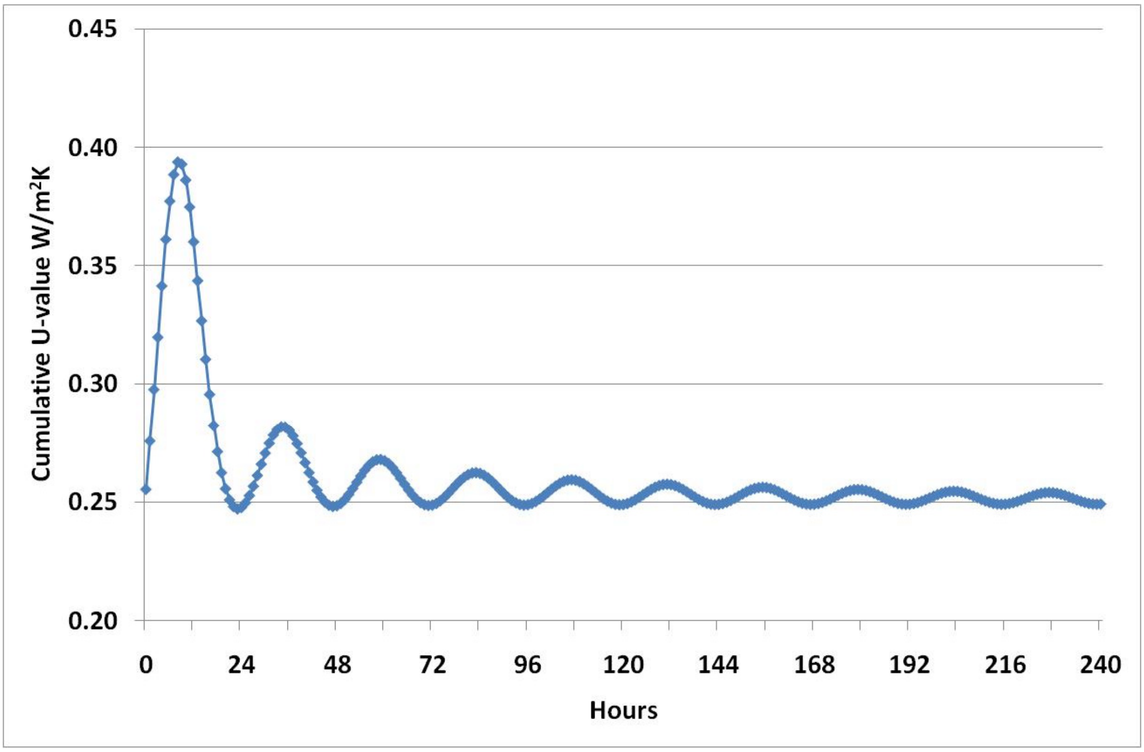


Figure 76 Wall 3 - Rolling average U-value



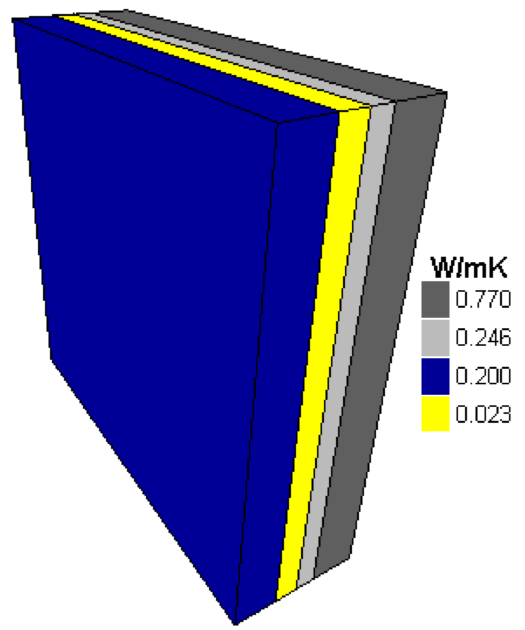
7.3.3 Wall 3 with plasterboard removed

Table 14 Details of materials in Wall 3 without plasterboard

Material	Width mm	Conductivity W/m·K	Density kg/m^3	Specific Heat J/kg·K
Block	100	0.15	600	1010
PUR	55	0.023	30	1400
Cavity	45	0.102*	1.2	1000
Brick	102	0.77	1750	1000

[*] Emissivity of PIR foil face assumed to be 0.2

Figure 77 Wall 3 without plasterboard - model and boundary conditions

	Model area = 1.0 * 1.0 = 1.0 m^2 Steady state Ti=22°C, Te = 9°C, Q = 3.420 W U = 0.263 W/m^2K Step change time constant = 6.35 hours Sinusoidal time lag = 9.5 hours Heat flow amplitude = 1.17 W Cumulative U-value = 0.263 W/m^2K

Heat flow into wall 3 with no plasterboard in response to step change of external temperature from 22°C to 9°C

Figure 78 Wall 3 – No plasterboard - Heat flow with step change of external temperature from 22°C to 9°C

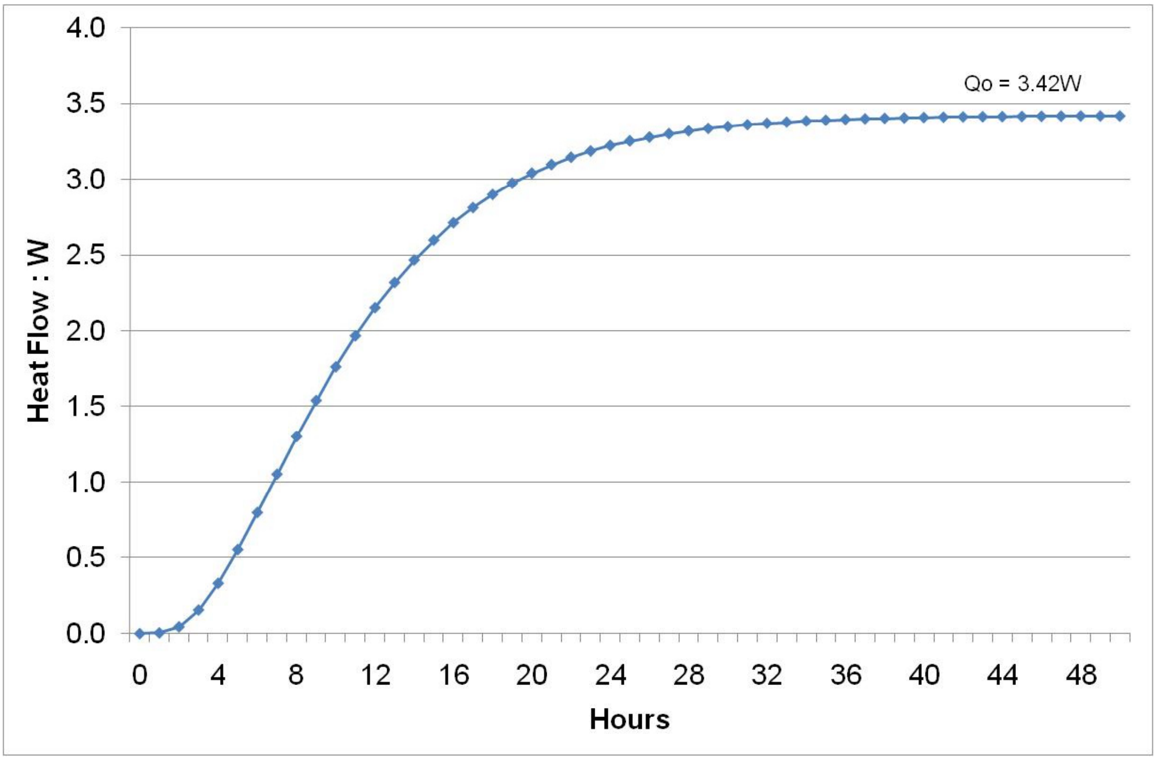


Figure 79 Wall 3 no plasterboard - Plot of log(Qo-Q(t)) against time

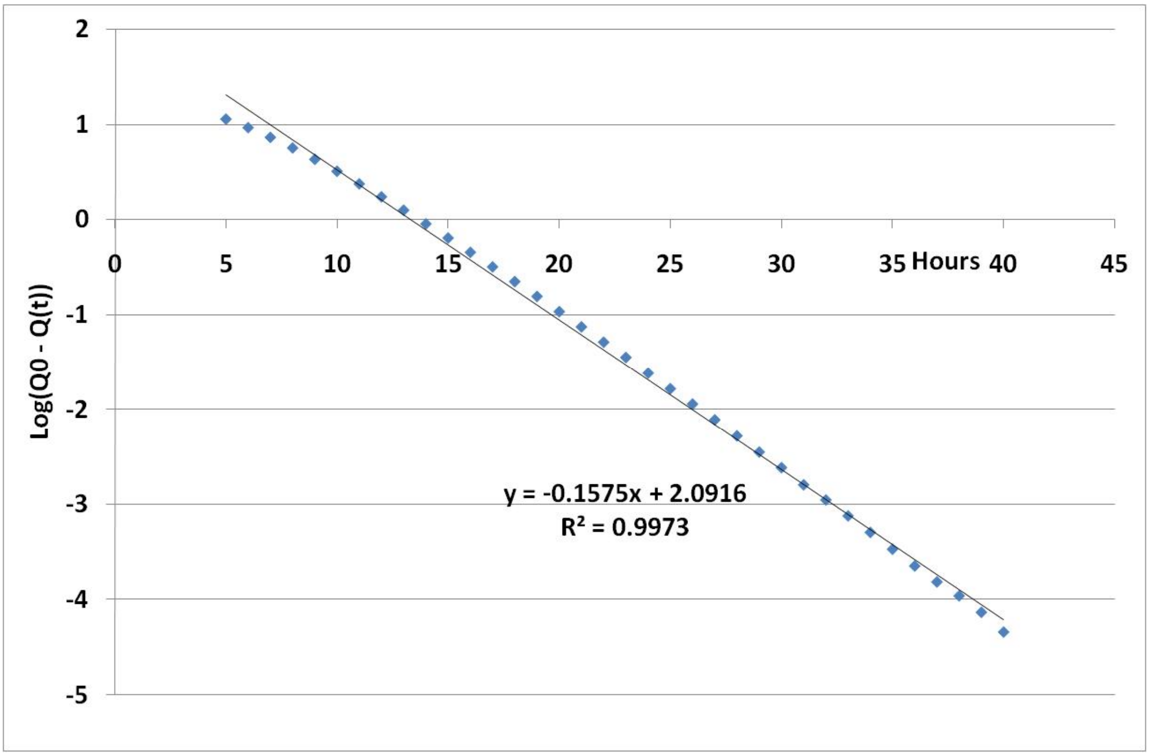


Figure 80 - Wall 3 no plasterboard - Heat flow with external sinusoidal temperature, internal temperature constant.

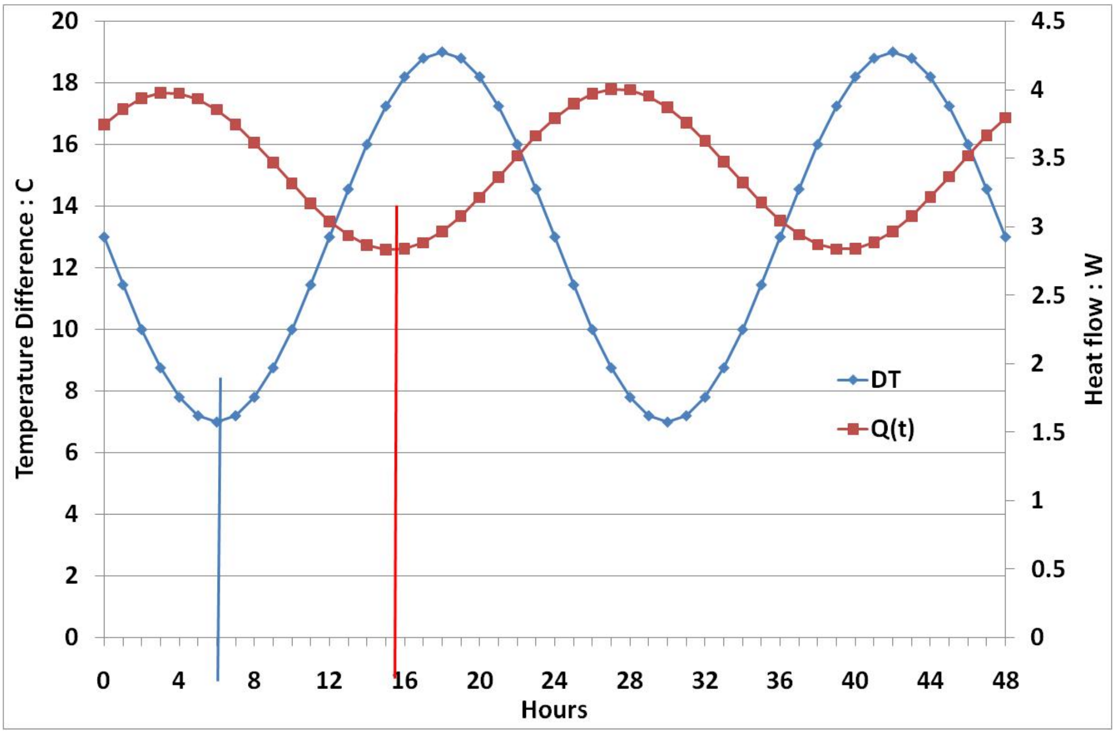
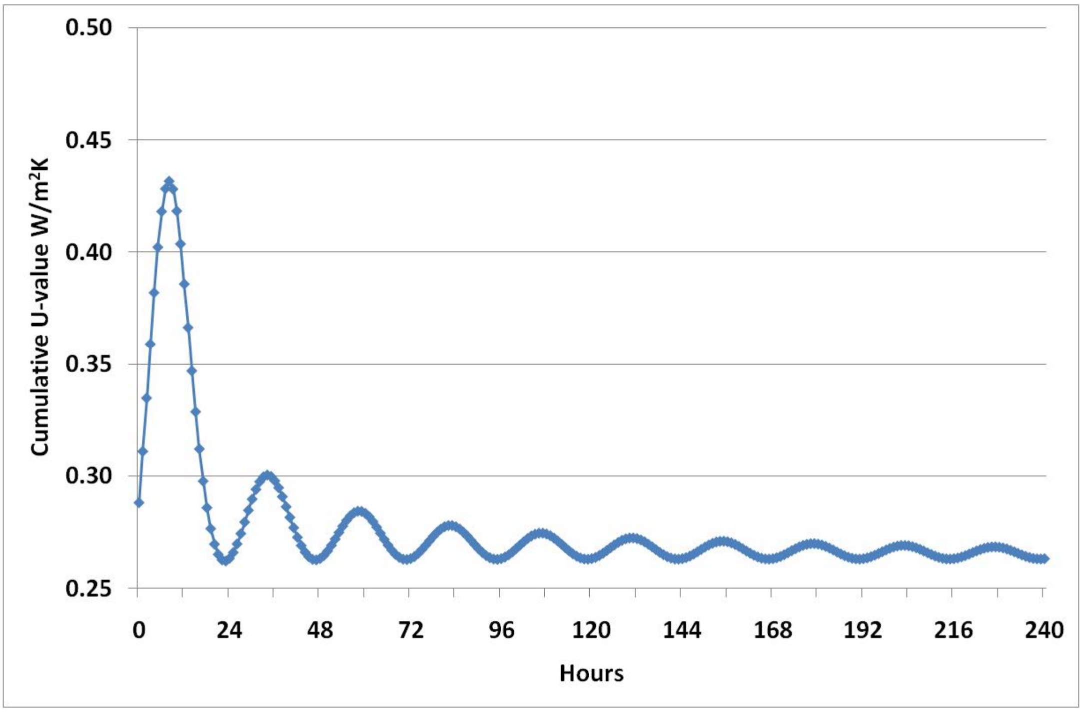


Figure 81 Wall 3 - no plasterboard - rolling average U-value.



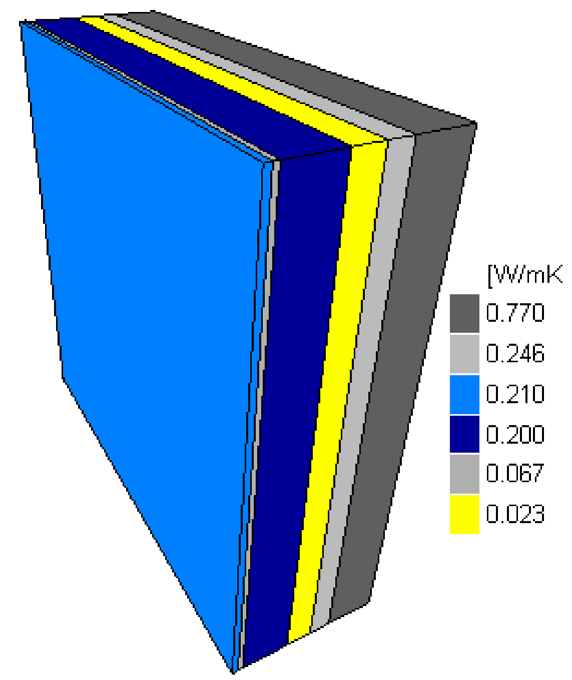
7.3.4 Wall 4 – ICF wall – Neopor & Steel connectors

Table 15 Details of materials in Wall 4

Material	Width mm	Conductivity W/m·K	Density kg/m^3	Specific Heat J/kg·K
Plasterboard	12.5	0.21	700	1000
Cavity	10	0.067	1.2	1000
Neopor	65	0.03	20	1400
Concrete	150	1.75	2400	1000
Neopor	65	0.03	20	1400
Render	9	0.85	1900	850
Steel ties	3	0.20	7800	480

Steel ties were assumed to be 3 mm dia. at 150mm centres in both directions, penetrating 53 mm into the insulation on both sides as steel ties in wall 1.

Figure 82 Wall 4 - model details and boundary conditions



Model area = 1.192 * 1.192 = 1.42m^2

Steady state Ti=22°C, Te = 9°C, Q = 4.168 W

U = 0.225 W/m^{2}K

Step change time constant = 109.8 hours

Sinusoidal time lag = 10 hours

Heat flow amplitude = 0.13 W

Cumulative U-value = 0.227 W/m^{2}K

Figure 83 Wall 4 Heat flow with step change of external temperature from 22°C to 9°C

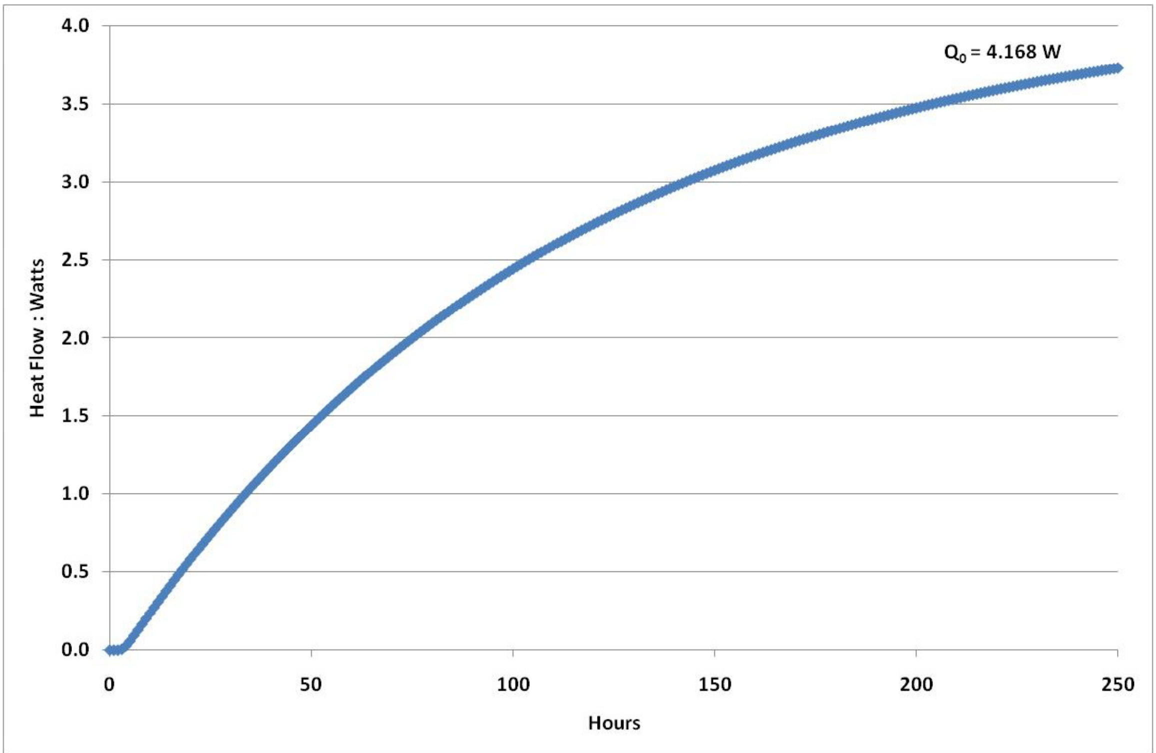


Figure 84 Wall 4 - Plot of log(Qo-Q(t)) against time

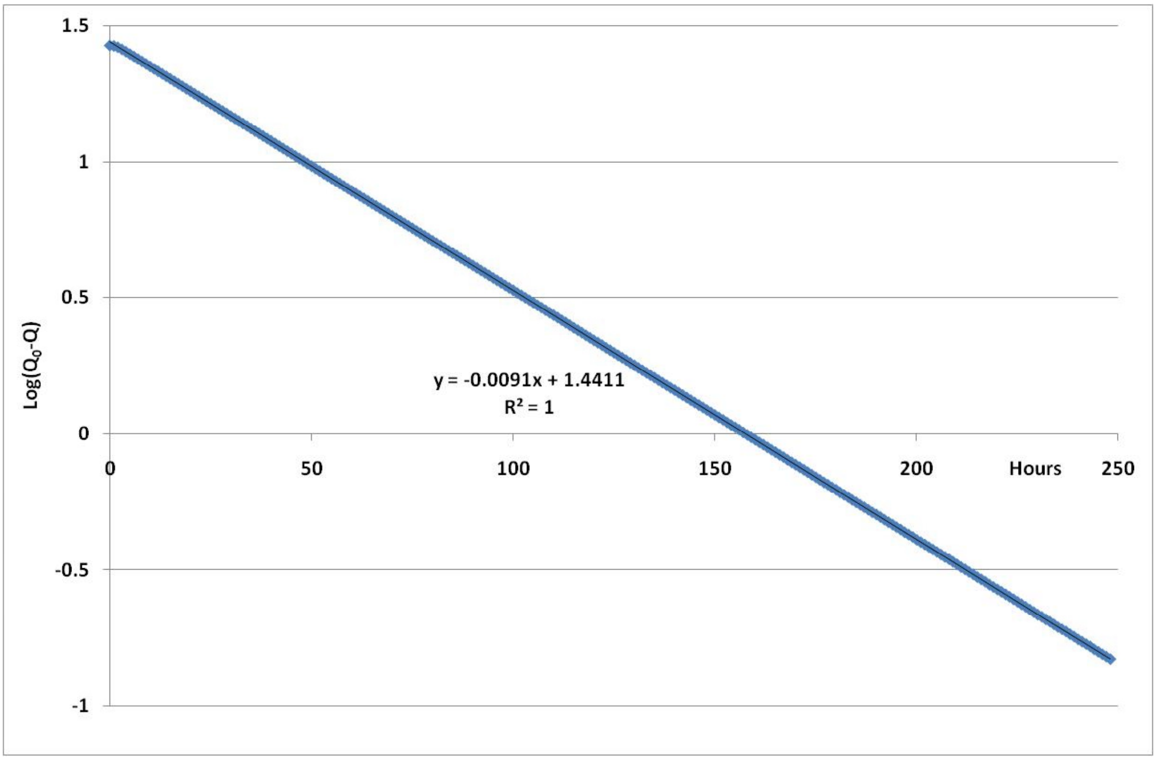


Figure 85 Wall 4 - Heat flow - external sinusoidal temperature, internal temperature constant.

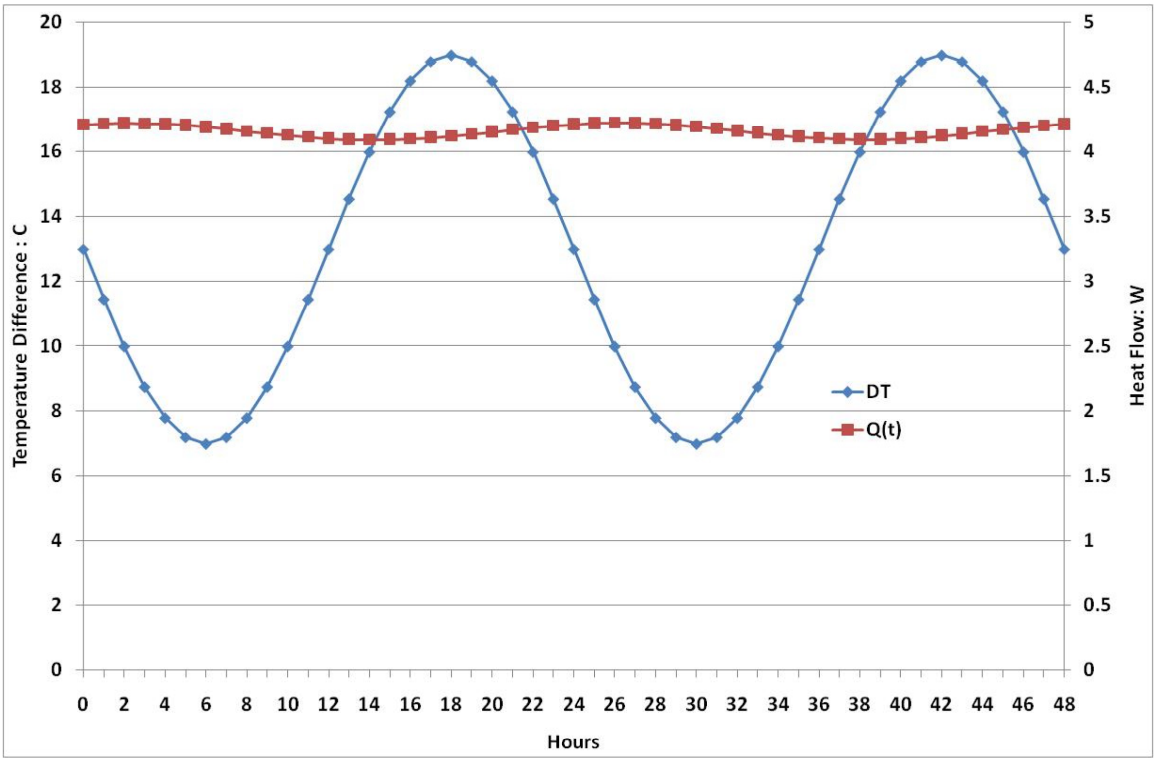
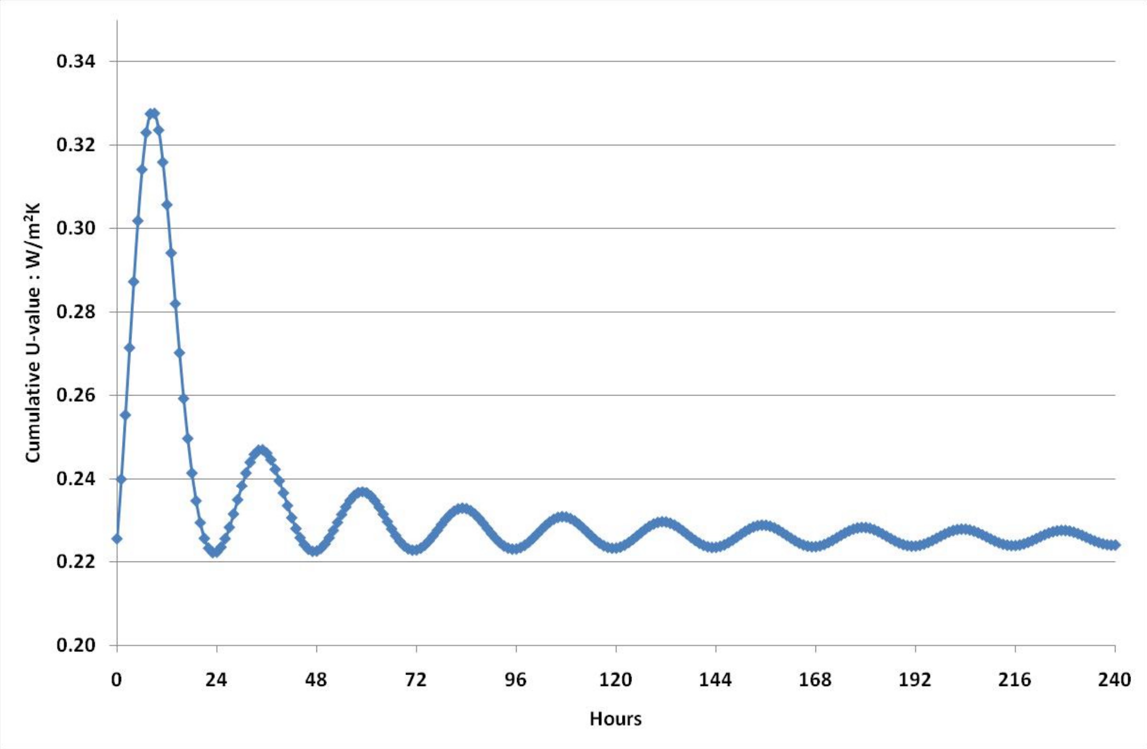


Figure 86 Wall 4 - Rolling average U-value



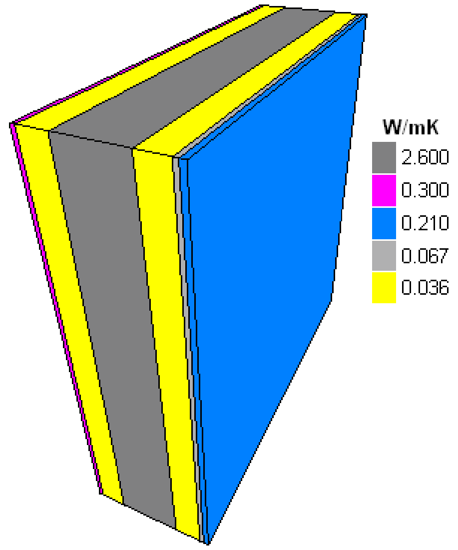
7.3.5 Wall 6 – ICF wall - EPS & Plastic connectors

Figure 87 Details of the materials used in Wall 6

Material	Width mm	Conductivity W/m·K	Density kg/m³	Specific Heat J/kg·K
Plasterboard	12.5	0.21	700	1000
Cavity	10	0.067	1.2	1000
EPS	65	0.034	24	1450
Concrete	150	1.7	2400	930
EPS	65	0.034	24	1450
Render	10	0.85	1900	850
Plastic ties	3 square	0.20	1400	1470

Plastic ties assumed to be 3mm square at 150mm centres in both directions, penetrating 53 mm into the insulation on both sides as steel ties in wall 1.

Figure 88 Wall 6 - model details and boundary conditions

<table>
<tr><td>
</td><td>Model area = 1.192 * 1.192 = 1.42m^2

Steady state Ti=22°C, Te = 9°C, Q = 4.30 W

U = 0.233 W/m^{2}K

Step change time constant = 106.4 hours

Sinusoidal time lag = 10 hours

Heat flow amplitude = 0.13 W

Cumulative U-value = 0.233 W/m^{2}K</td></tr>
</table>

Figure 89 - Wall 6 heat flow with a step change of external temperature from 22°C to 9°C

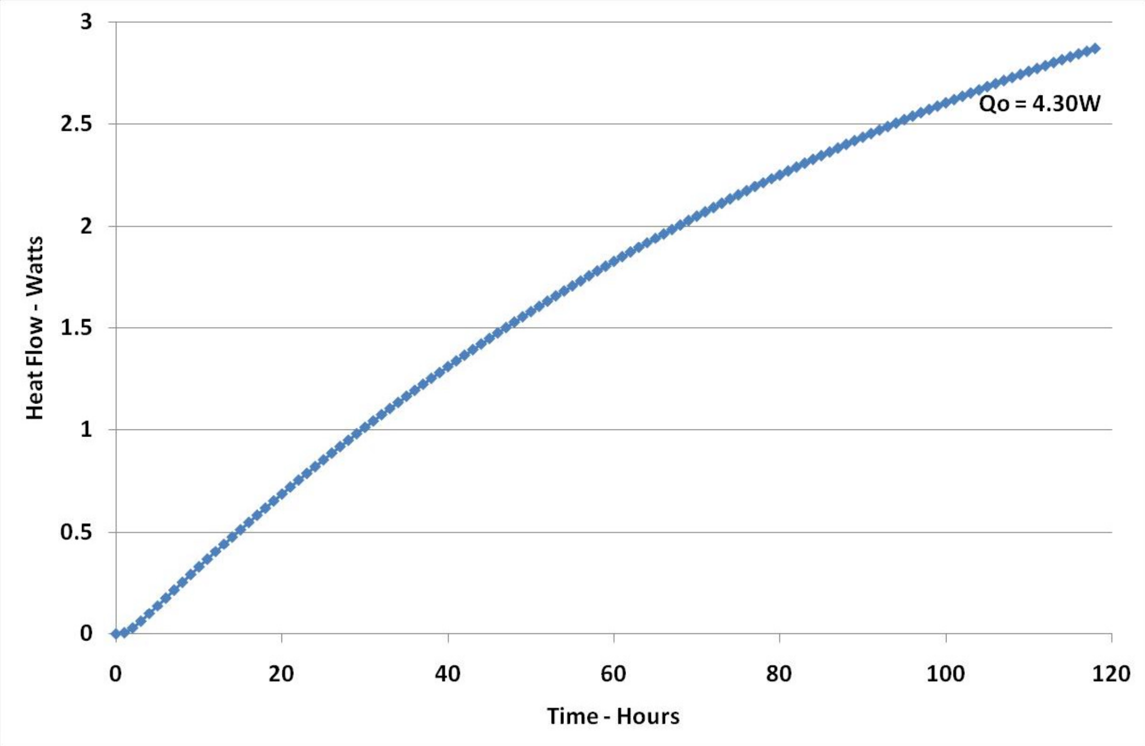


Figure 90 Wall 6 - Plot of log(Qo-Q(t)) against time

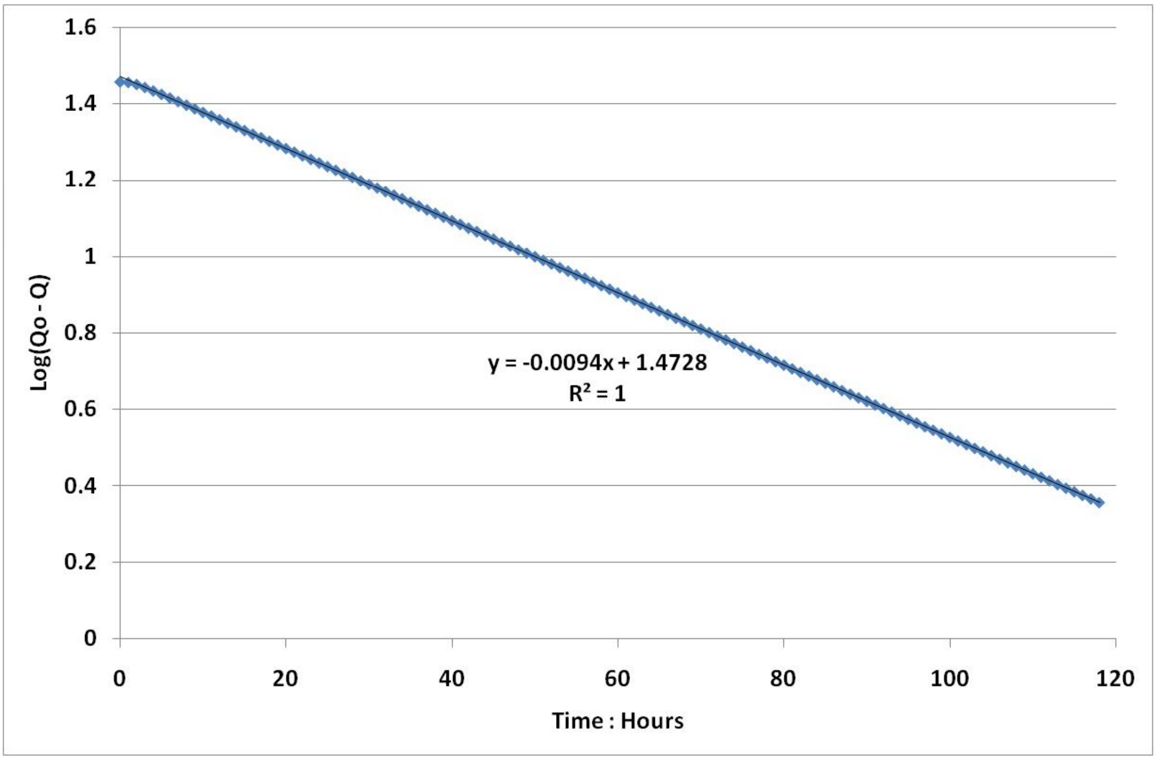


Figure 91 Wall 6 - Heat flow - external sinusoidal temperature, internal temperature constant.

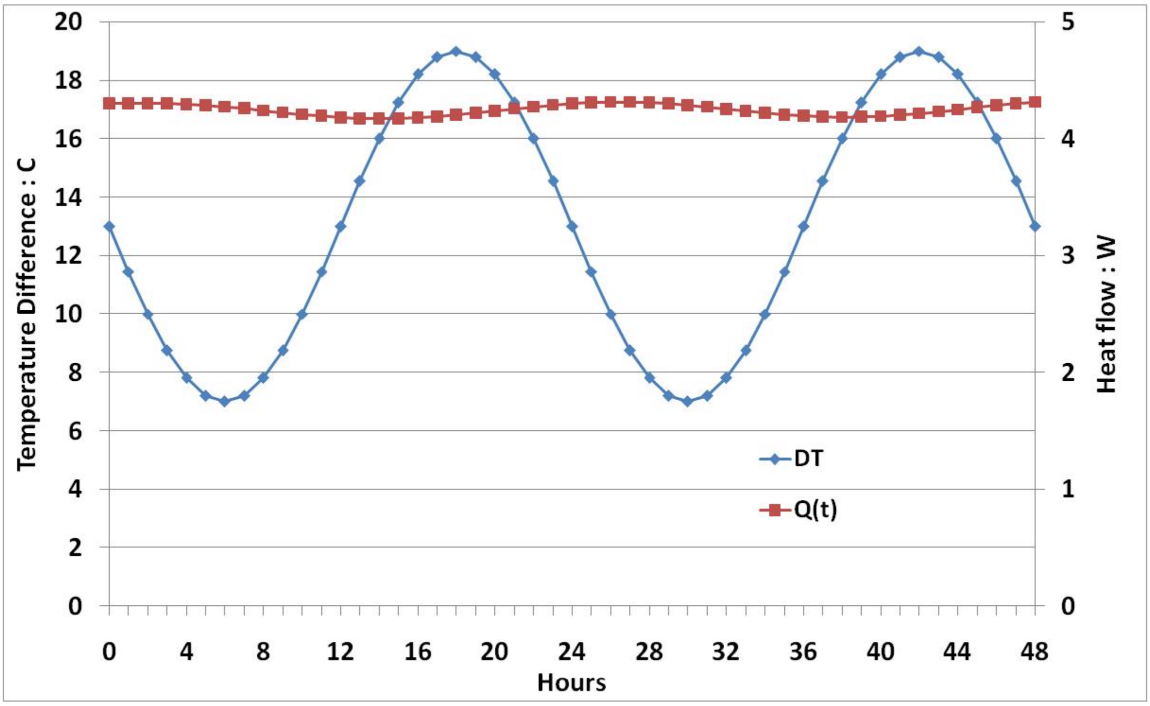
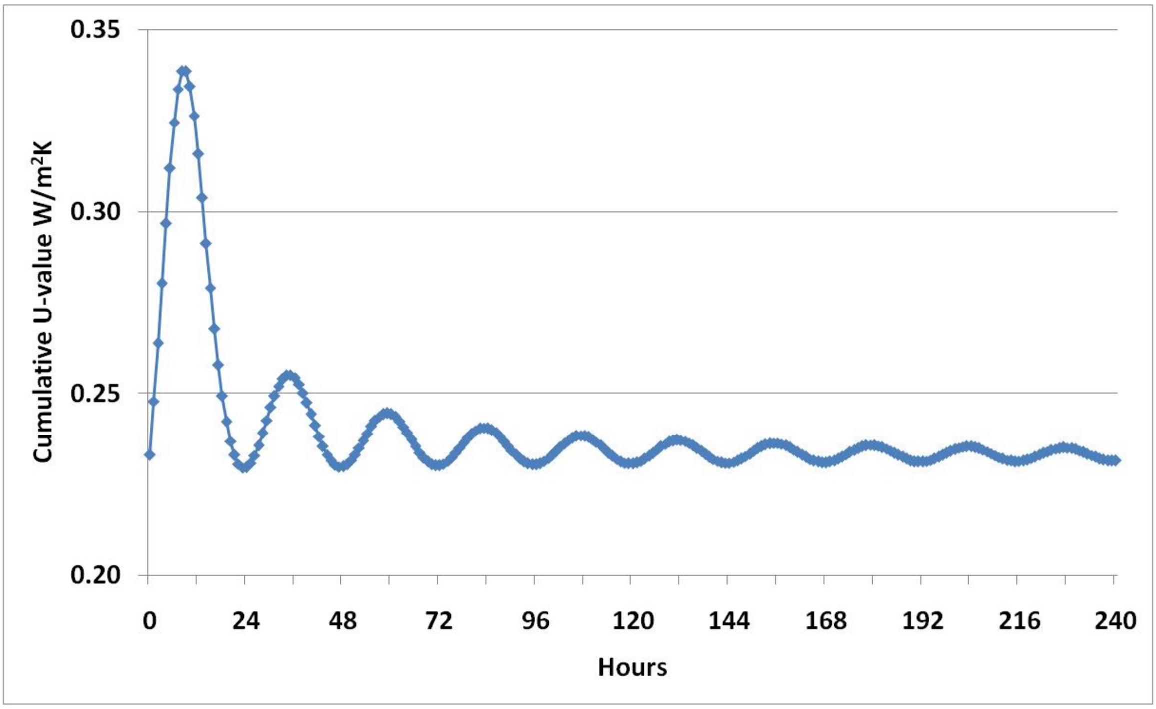


Figure 92 Wall 6 - Rolling average U-value

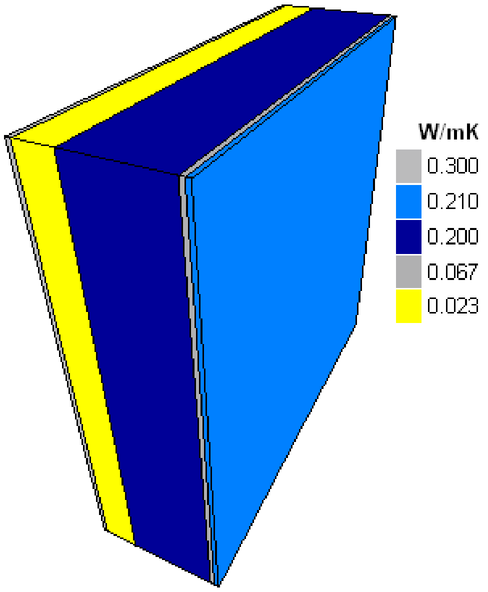


7.3.6 Wall 7 – AAC / PIR / Plasterboard

Table 16 Details of the materials used in Wall 7

Material	Width mm	Conductivity W/m·K	Density Kg/m³	Specific Heat J/kg·K
Plasterboard	12.5	0.21	700	1000
Cavity	10	0.067	1.2	1000
Concrete	200	0.11	600	1000
Insulation	80	0.023	30	1400
Render	9	0.85	1900	850

Figure 93 Wall 7 Model details and boundary conditions



Model area = 1.0 * 1.0 = 1.00m^2

Steady state Ti=22°C, Te = 9°C Q = 2.286 W

U = 0.176 W/m^{2}K

Step change time constant = 14.9 hours

Sinusoid time lag =10 hour

Heat flow amplitude = 0.82 W

Cumulative U-value = 0.1.76 W/m^{2}K

Figure 94 Wall 7 - Heat flow with step change of external temperature from 22°C to 9°C

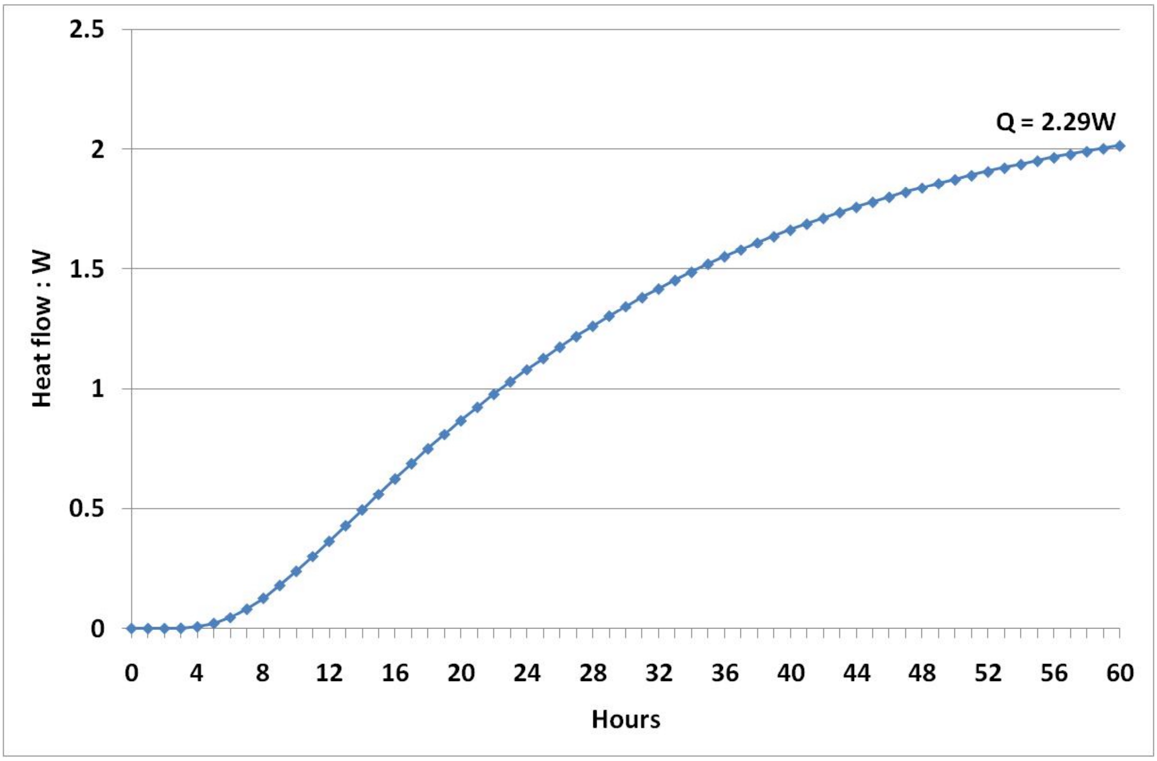


Figure 95 Wall 7 - Plot of log(Qo-Q(t)) against time

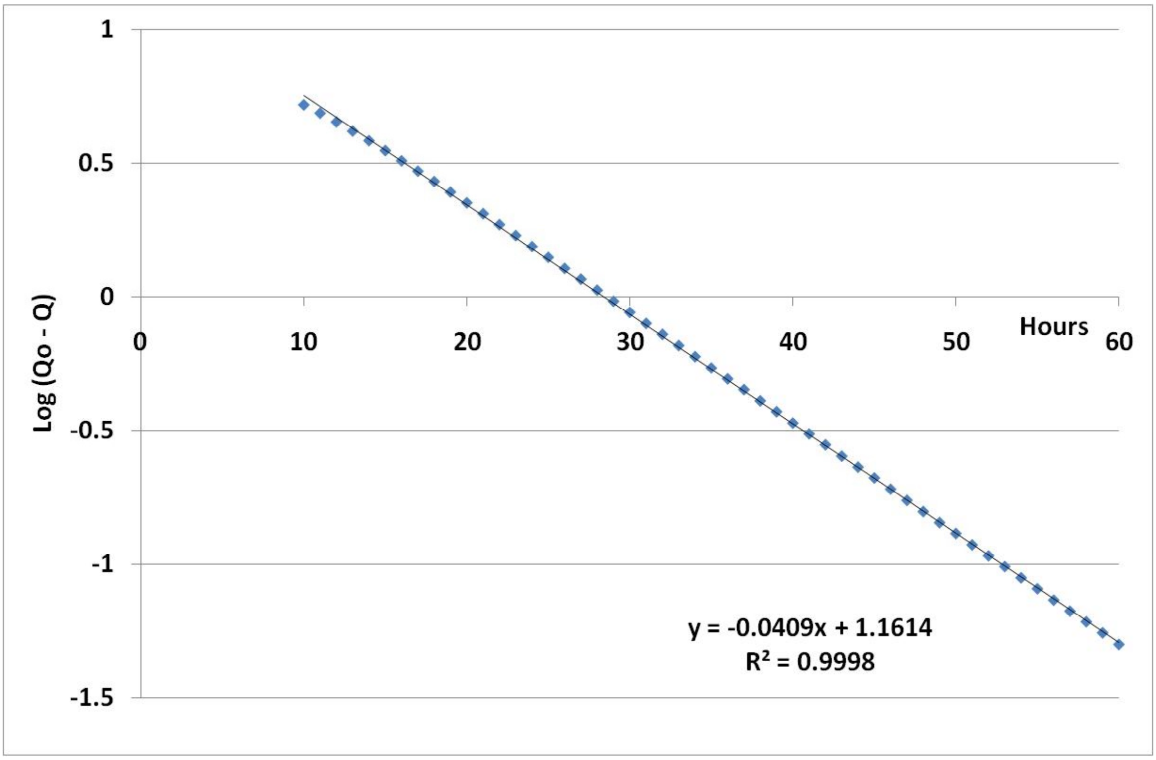


Figure 96 Wall 7 - Heat flow -external sinusoidal temperature, internal temperature constant

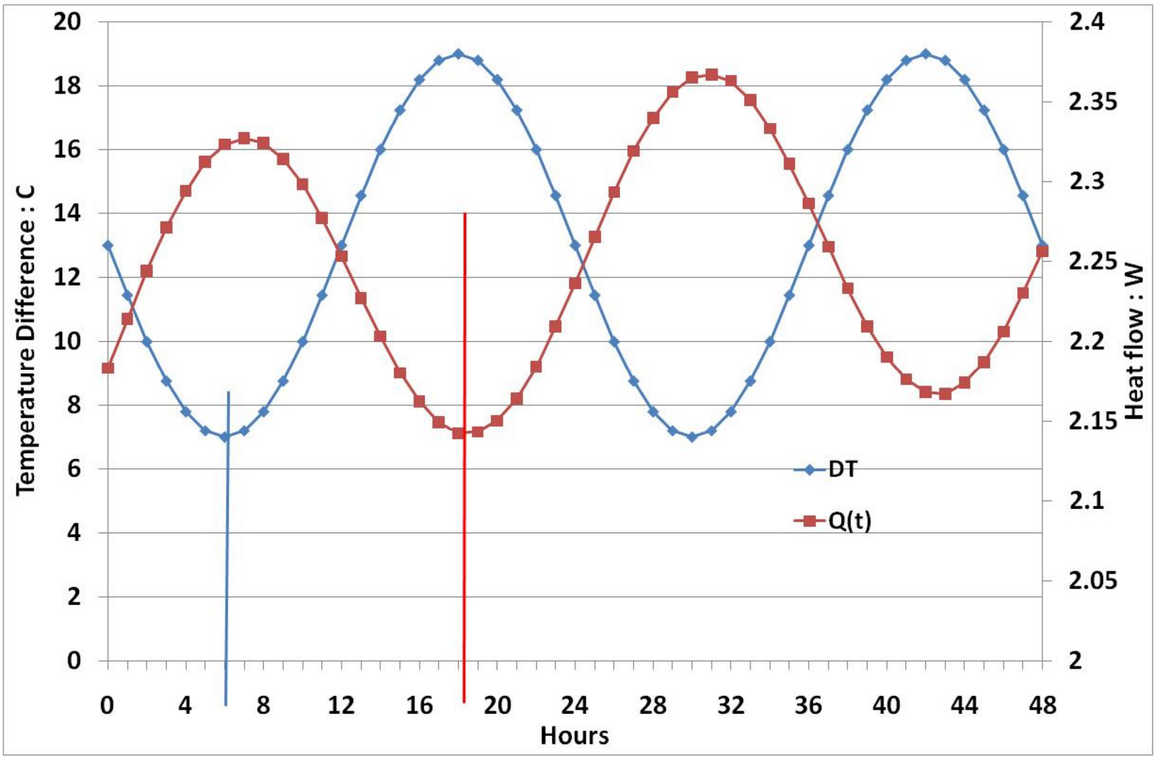
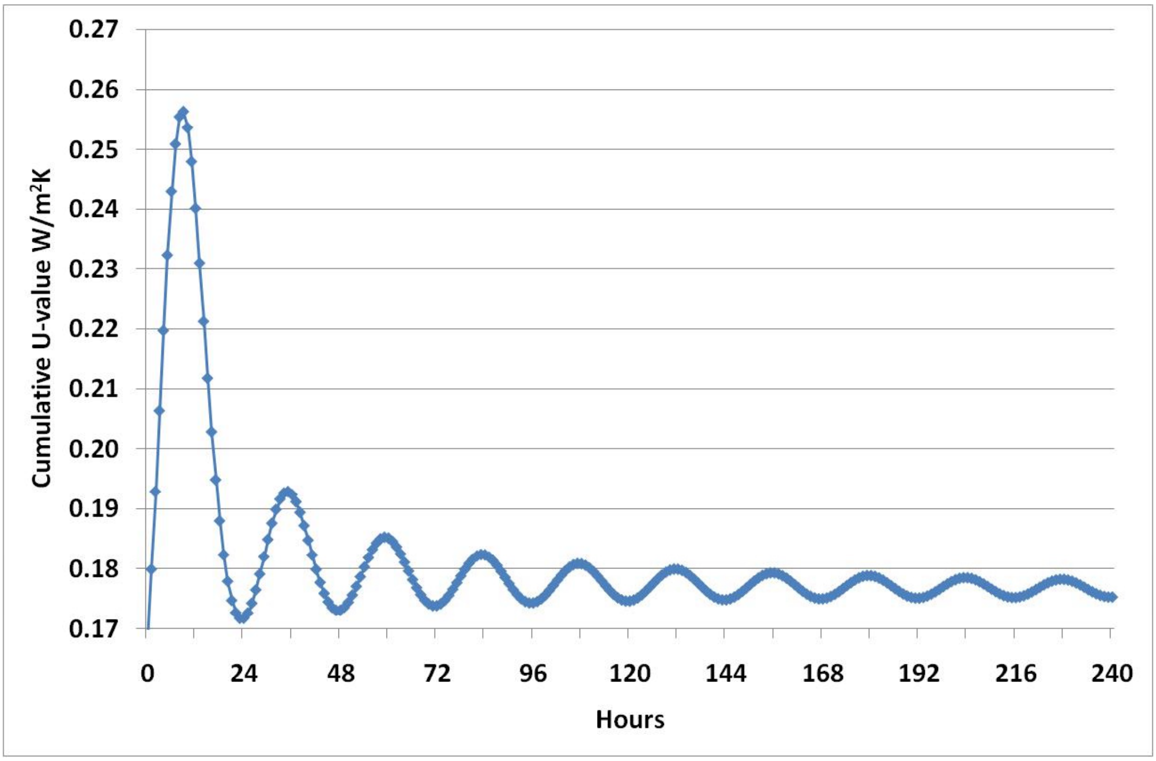


Figure 97 Wall 7 - Rolling average U-value



7.3.7 Wall 8 – Brick / PIR / lightweight aggregate blocks / plasterboard

Table 17 Details of materials in Wall 8

Material	Width mm	Conductivity W/m·K	Density Kg/m^3	Specific Heat J/kg·K
Plasterboard	12.5	0.21	700	1000
Cavity	10	0.067	1.2	1000
Block	100	0.47	1450	1000
Insulation	55	0.023	30	1400
Cavity	45	0.102*	1.2	1000
Brickwork	102	0.77	1750	1000
Render	9	0.3	1900	850

Figure 98 Details of the model and boundary conditions

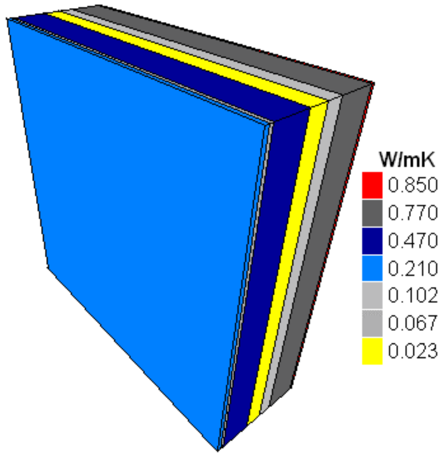
	Model area = 1.0 * 1.0 = 1.00m^2 Steady state Ti=22°C, Te = 9°C Q = 3.65 W U = 0.280 W/m^{2}K Step change time constant = 15.0 hours Sinusoid time lag =11 hour Heat flow amplitude = 0.51 W Cumulative U-value = 0.280 W/m^{2}K

Figure 99 Wall 8 - Heat flow with a step change of external temperature from 22°C to 9°C

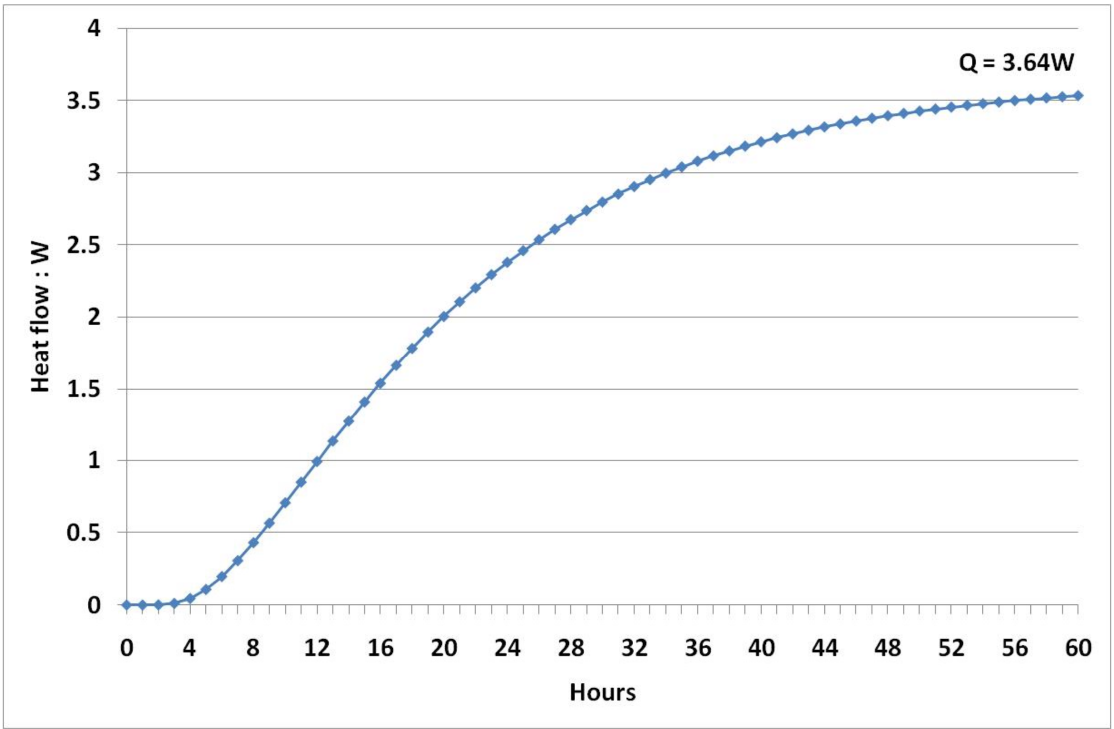


Figure 100 Wall 8 - Plot of log(Qo-Q(t)) against time

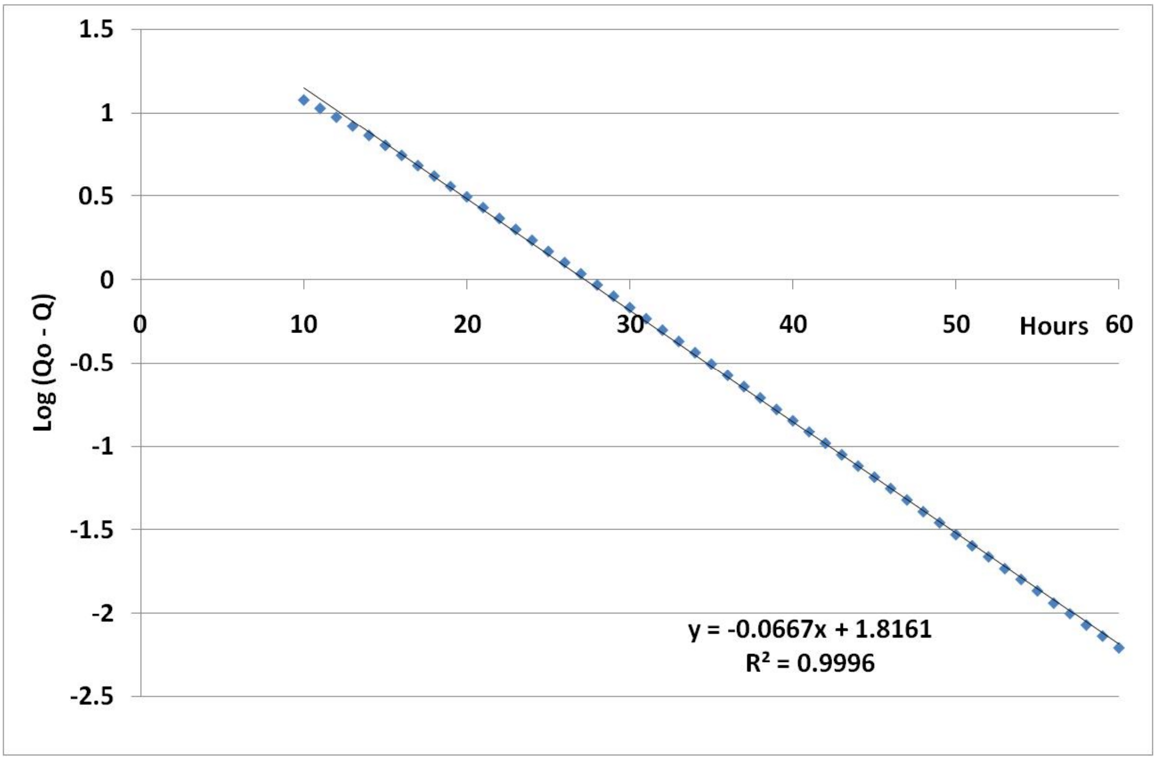


Figure 101 Wall 8 - Heat flow - external sinusoidal temperature, internal temperature constant

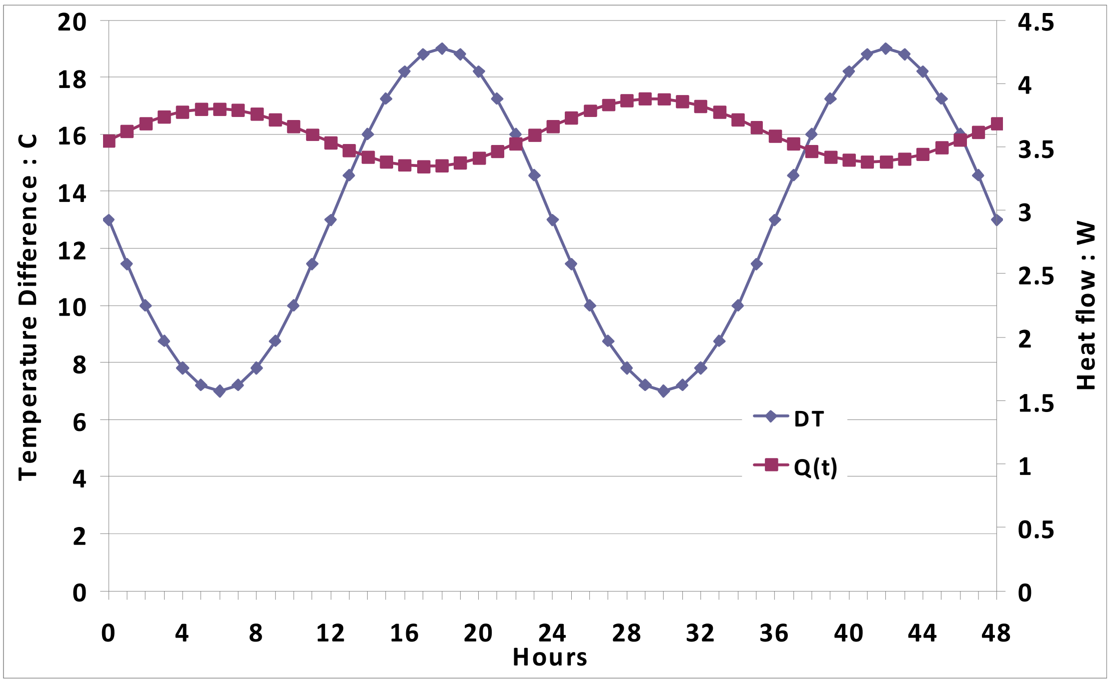
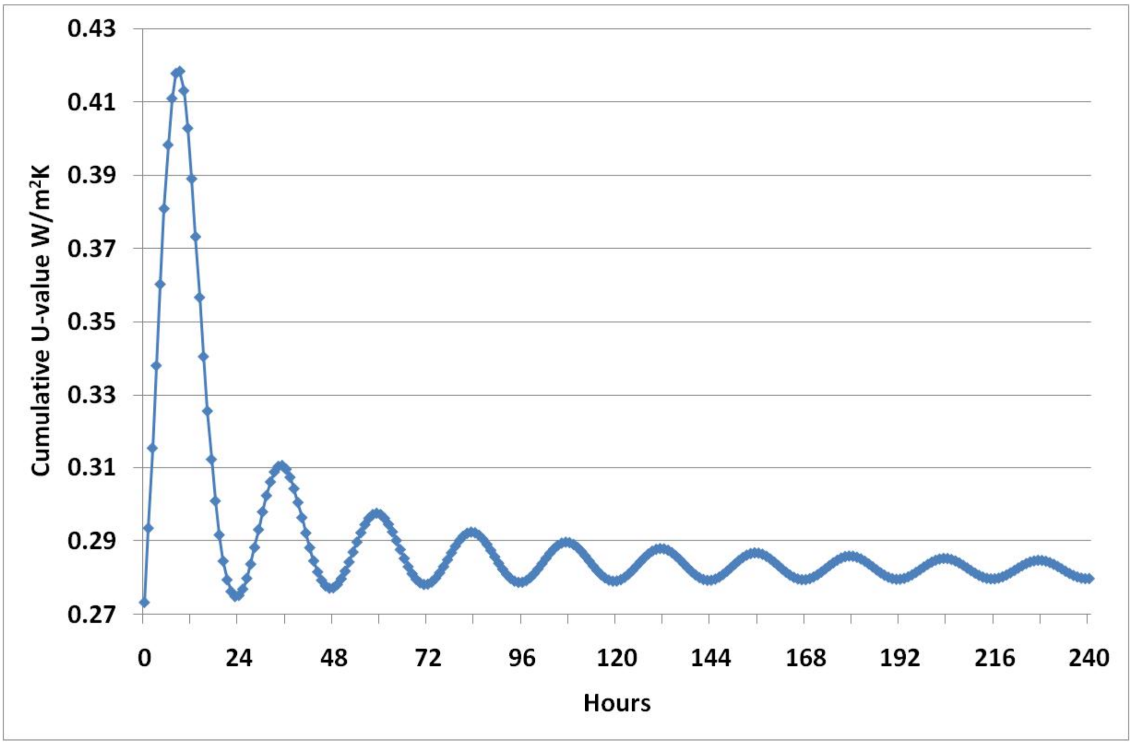


Figure 102 Wall 8 - Rolling average U-value



7.4 Summary of heat transfer modelling results.

The results from the above calculations are summarised in Table 18 and the relevant values included in Table 10.

Table 18 Summary of heat transfer modelling results

Wall	Steady state U-value W/m^2K	Step change time constant Hours	Sinusoidal time lag Hours	Heat flow amplitude W	Cumulative U-value W/m^2K
1: ICF Polysteel	0.252	98.0	12	0.16	0.252
2: Timber framed	0.230	7.0	4	1.52	0.230
3: Brick, PIR & AAC & plasterboard	0.249	8.6	10	0.82	0.249
3: Brick, PIR & AAC - No plasterboard	0.263	6.4	9.5	1.17	0.263
4: ICF Polysteel	0.269	91.7	10	0.18	0.269
6: Polysteel	0.232	106.3	10	0.13	0.232
7: AAC / Celatex /	0.176	14.9	10	0.82	0.176
8: Brick/Insulation/ light aggregate	0.280	15.0	11	0.51	0.280

7.5 Details of the temperature profile modelling

7.5.1 Overview of temperature profile modelling

Modelling the temperature profiles has been carried out for walls 3 & 8. That modelling concentrated on replicating the temperatures at the interfaces between materials measured in the tests at NPL, given the 'hot' and 'cold' air temperatures recorded at NPL. Material property data have been taken from the information provided supplemented with further information from Anderson[1].

Air cavities have been assigned an equivalent thermal conductivity depending on their width and the thermal resistance derived from the EN ISO 6946 rules, taking account of the surface emissivities.

The standard EN ISO 6946 internal and external surface resistances were assumed, i.e:
'Hot' R_{si} = 0.13 m^2K/W, 'Cold' R_{se} = 0.04 m^2K/W.

The models were generated with Voltra and were made up of 1 metre square wall sections, consisting of a series of parallel layers. No account was taken, at this stage, of bridging due to mortar, wall ties or timber studs behind the plasterboard.

7.5.2 Material properties used for Walls 3 and 8

Table 19 Material properties for Wall 3

Brick	thickness	102	Mm	Sand faced flettons
	Density	1750	kg/m^3	
	Specific heat	850	J/kgK	Voltra Database
	thermal conductivity	0.77	W/m.K	CIBSE Guide A
Air cavity	thickness	45	mm	
	density	1.2	kg/m^3	Anderson
	Specific heat	1000	J/kgK	Anderson
	thermal conductivity	0.102	W/m.K	6946 rules e=0.2 on one side
Insulation	thickness	55	mm	Celotex CW3055 Foil faced
	density	30	kg/m^3	
	Specific heat	1470	J/kgK	Anderson
	Thermal conductivity	0.023	W/m.K	Manufacturers data
AAC blocks	thickness	100	mm	Celcon
	density	600	kg/m^3	
	Specific heat	1010	J/kgK	Voltra database
	Thermal conductivity	0.15	W/m.K	Manufacturers data
Air cavity	thickness	10	mm	
	density	1.2	kg/m^3	Anderson
	Specific heat	1000	J/kgK	Anderson
	thermal conductivity	0.067	W/m.K	6946 rules e=0.9 on both sides
Plasterboard	thickness	12.5	mm	
	density	700	kg/m^3	Data taken from CIBSE Guide A
	Specific heat	1000	$J.kg^{-1}.K^{-1}$	Data taken from CIBSE Guide A
	thermal conductivity	0.21	W/m.K	Data taken from CIBSE Guide A

Table 20 Material properties for Wall 8

Aggregate block	type			Celcon
	thickness	100	mm	
	density	1450	kg/m^3	
	Specific heat	910	J/kgK	Voltra database
	Thermal conductivity	0.47	W/m.K	Manufacturers data

7.5.3 Results of the temperature profile modelling of walls 3 & 8

The temperatures of the various material interfaces that were measured have also been simulated using Voltra for Wall 3 both with and without the plasterboard and for Wall 8 with plasterboard. The results are shown below in Figure 103, Figure 104 and Figure 105.

Figure 103 Wall 3 with Plasterboard – calculated temperature profiles

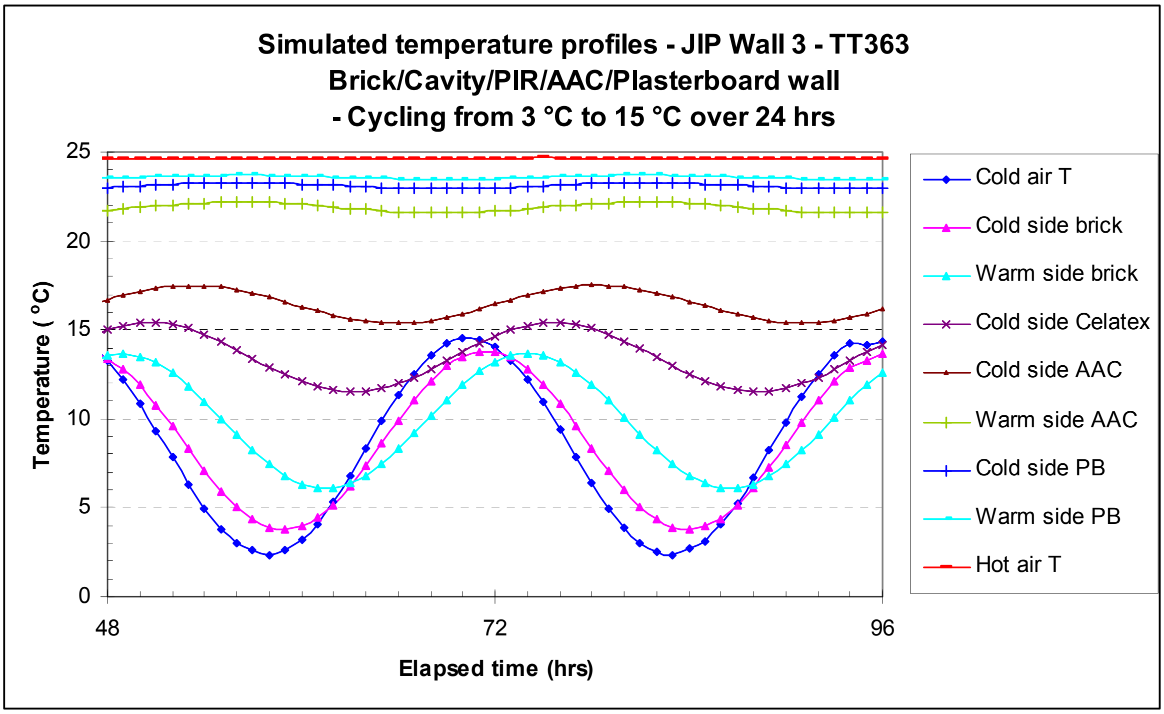


Figure 104 Wall 3 No plasterboard – calculated temperatures profiles.

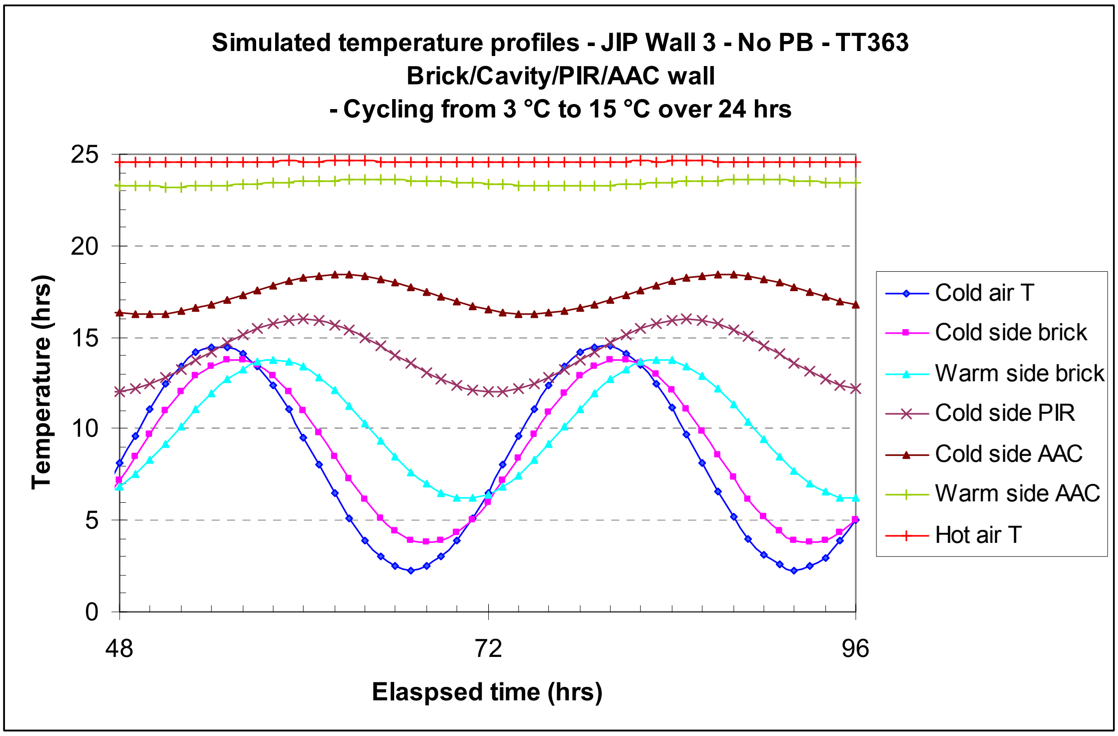
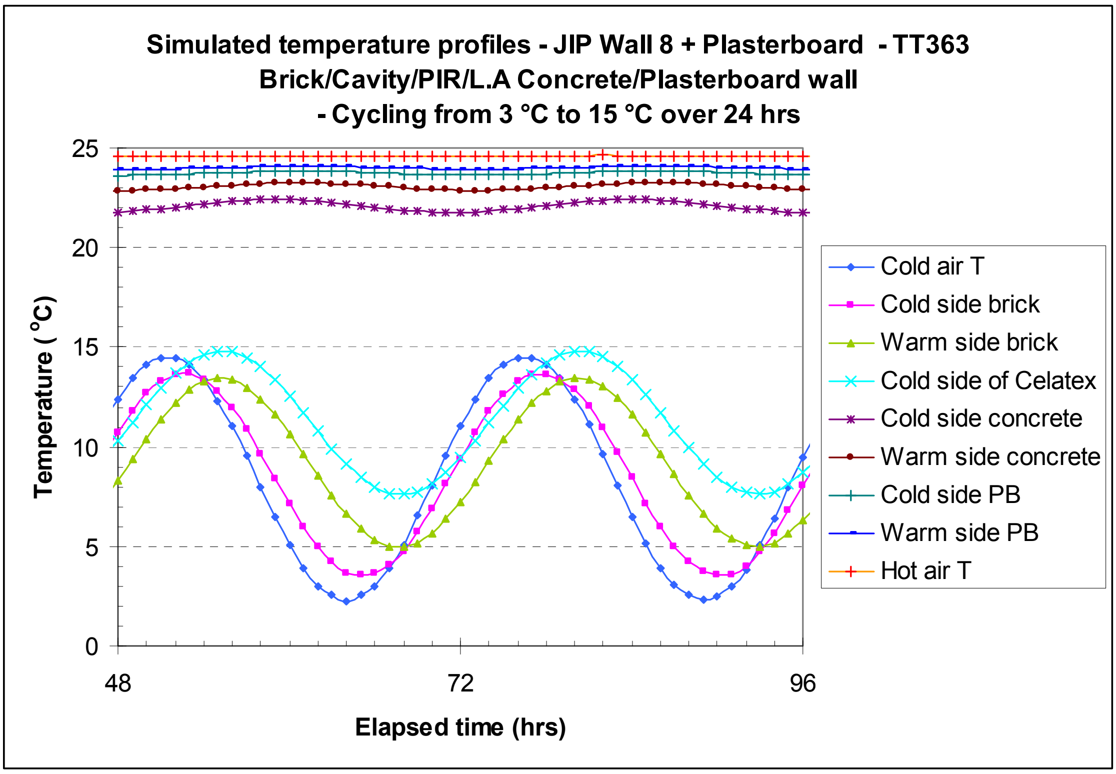


Figure 105 Wall 8 + plasterboard – calculated temperatures



8 DISCUSSION OF THE MEASURED AND CALCULATED VALUES

8.1 SUMMARY OF PROPERTIES MEASURED AND CALCULATED

The following properties were derived in one or more of the following ways:

i) from the total measured power into the warm chamber of the Hot Box apparatus by deducting the power transferred through the EPS surround panel.

ii) from the power through the walls that was measured with the 250 mm x 250 mm calibrated heat flow meter.

iii) Calculated using the Physibel Voltra 3D FEA dynamic software:

a) Energy (Wh) required maintaining the temperature of the warm chamber air temperature at 24 °C over one complete cycle.

b) Time lag between the maximum temperature difference between the cold chamber and warm chamber and the resulting maximum power transfer through the wall.

c) Amplitude of the variation in power transfer through the test element caused by the temperature cycling of the cold chamber.

d) Time lag between the minimum cold face surface temperature (the driver) and the minimum hot face surface temperature (responding to the cold face temperature). Note: the fluctuation in the hot face temperatures is very small.

e) The steady state U-value of the wall using the procedures specified in BS EN ISO 8990.

The values of parameters a, b, c and d are shown in Table 21 which compares the results derived in the different ways..

The method of using the power supplied to the hot chamber is intrinsically superior to using the power measured by the HFM because the power through the whole of the wall is being measured not just through the small portion of the wall covered by the HFM. The method of extracting the power through the wall from the total power being transferred through the wall plus the EPS surround panel is quiet complex for the cycling measurements.

Table 21 Values of Energy, power lag, temperature lag and power amplitude

Wall identity	% diff (WGHB-HFM)/WGHB %	Measured energy per 25 hr cycle over 12 °C (Wh)	% diff (WGHB-HFM)/WGHB %	% diff (WGHB-Voltra)/WGHB %	% diff (HFM -Voltra)/HFM %	Measured amplitudeof variation in power (Watts)	% diff (WGHB-HFM)/WGHB %	% diff (WGHB -Voltra)/WGHB %	% diff (HFM -Voltra)/HFM %	Measured lag - max temp diff to max power (hours)	Measured lag - min cold face temp to min hot face temp. (hours)	Ratio: Temperature lag time to power lag time	Source of value
Wall 1 - ICF	2.2	182 178 n/a	33.3	67	50	0.36 0.24 0.12	53.3	44	-20	21.4 10.0 12.0	30.2	1.4	**WGHB** **HFM** **Voltra**
Wall 2 - Timber	n/a	153 n/a n/a	n/a	36	51	2.38 3.10 1.52	n/a	17	n/a	4.8 n/a 4.0	5.0	1.0	**WGHB** **HFM** **Voltra**
Wall 3 Brick + PB	9.4	157 142 n/a	-7.7	-63	-51	0.65 0.70 1.06	1.8	9	7	11.0 10.8 10.0	8.2	0.7	**WGHB** **HFM** **Voltra**
Wall 3 - Brick No PB	n/a	170 n/a n/a	4.8	n/a	n/a	1.65 1.57 n/a	13.6	n/a	n/a	11.0 9.5 n/a	7.5	0.7	**WGHB** **HFM** **Voltra**
Wall 4 - ICF	1.2	170 168 n/a	18.8	44	31	0.32 0.26 0.18	53.8	55	3	22.3 10.3 10.0	28.5	1.3	**WGHB** **HFM** **Voltra**
Wall 6 - ICF	1.5	159 157 n/a	60.0	70	25	0.40 0.16 0.12	52.6	53	2	21.5 10.2 10.0	27.0	1.3	**WGHB** **HFM** **Voltra**
Wall 7 - AAC	3.9	123 118 n/a	-18.2	-12	5	0.33 0.39 0.37	24.7	40	20	16.6 12.5 10.0	11.0	0.7	**WGHB** **HFM** **Voltra**
Wall 8 + Concrete & PB	4.2	167 160 n/a	-59.6	-9	32	0.47 0.75 0.51	10.2	7	-4	11.8 10.6 11.0	7.7	0.7	**WGHB** **HFM** **Voltra**
Wall 8 - Concrete & No PB	n/a	182 n/a n/a	n/a	n/a	n/a	1.03 n/a n/a	n/a	n/a	n/a	9.0 n/a n/a	7.5	0.8	**WGHB** **HFM** **Voltra**

Figure 106 Comparison between energy derived from hot-box power and HFM power

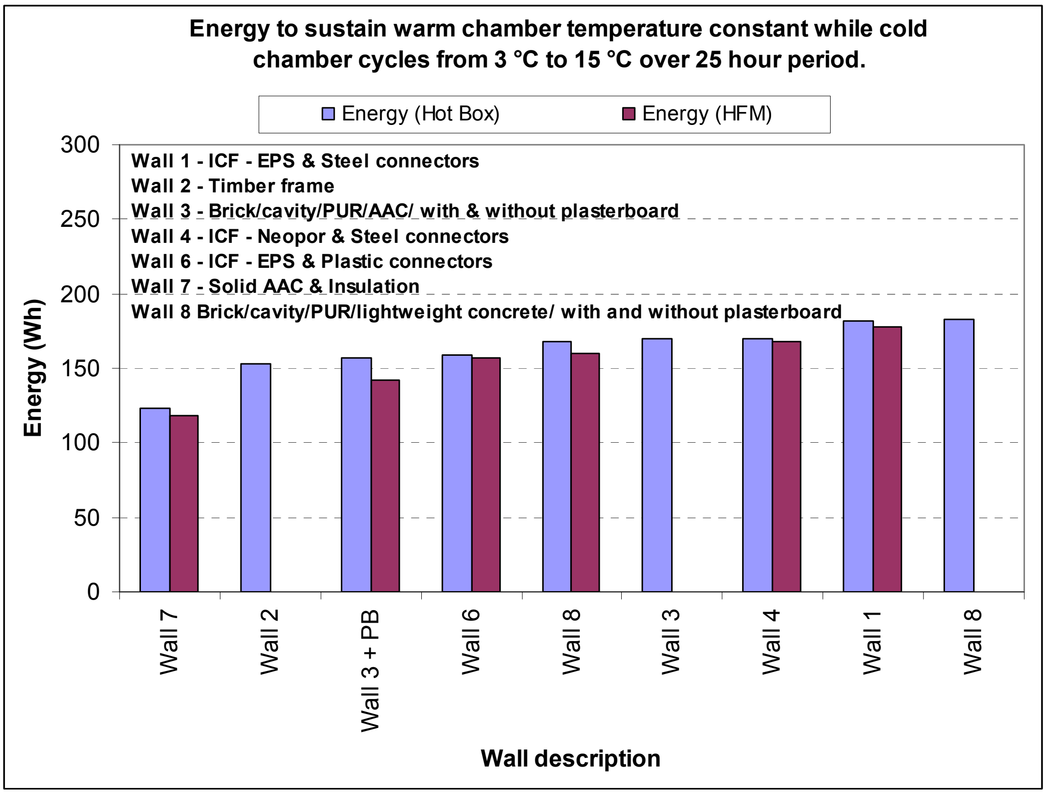


Figure 107 Comparison between lag times derived from hot-box, HFM and Voltra powers

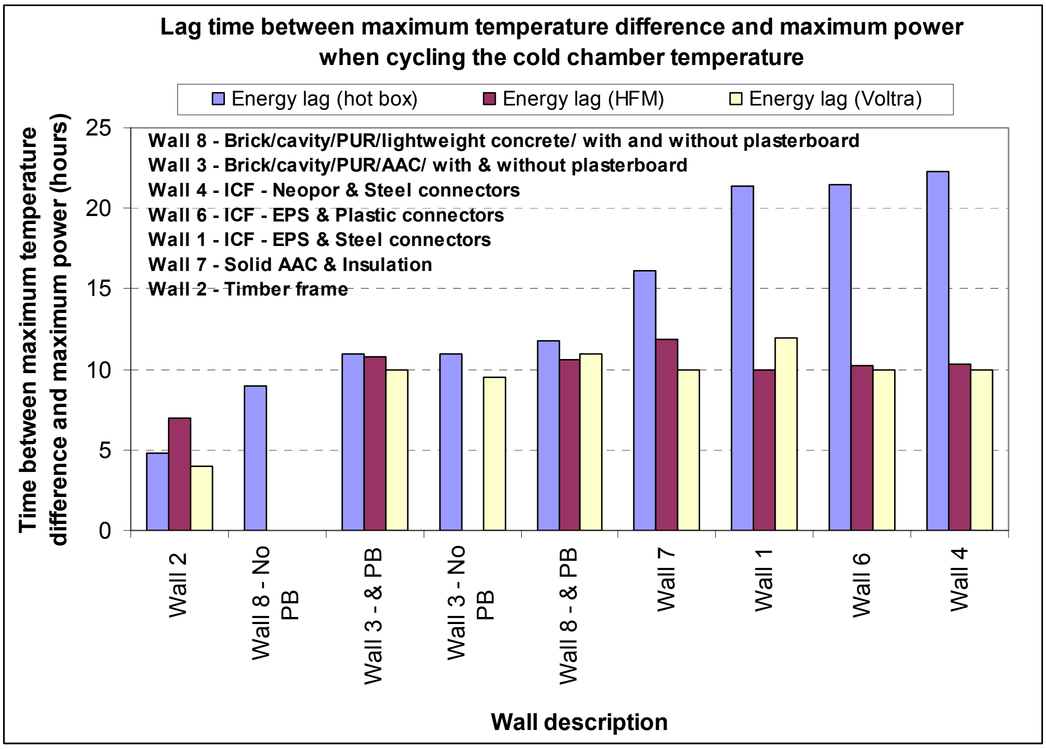
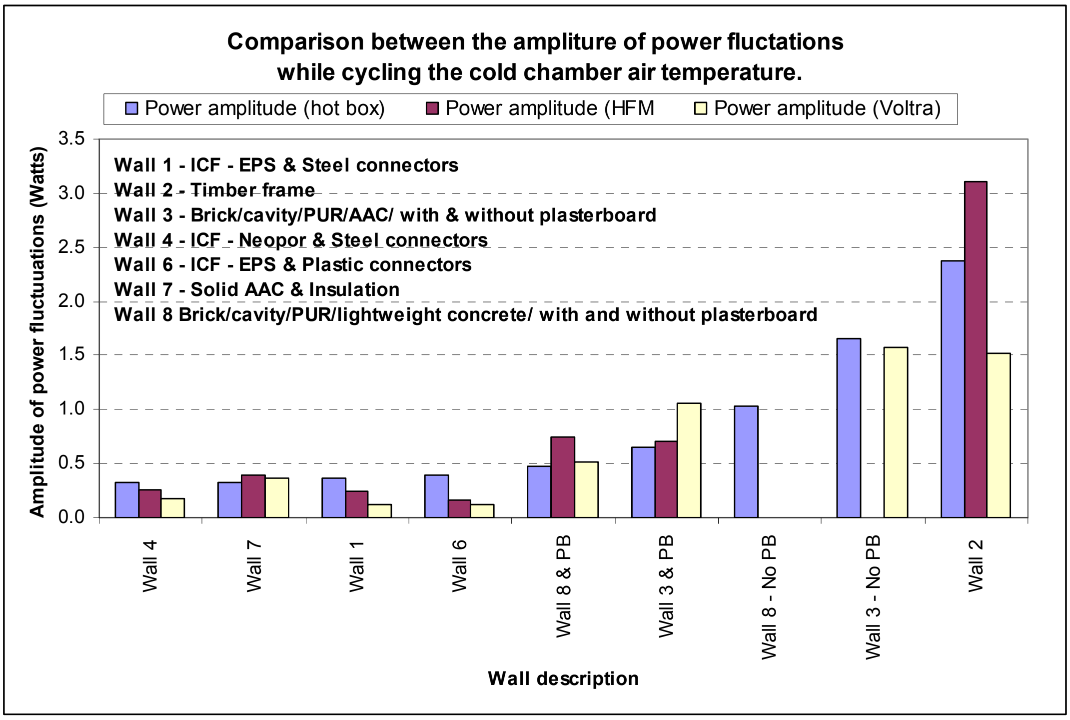


Figure 108 Comparison between amplitude of power fluctuations Hot-box, HFM & Voltra



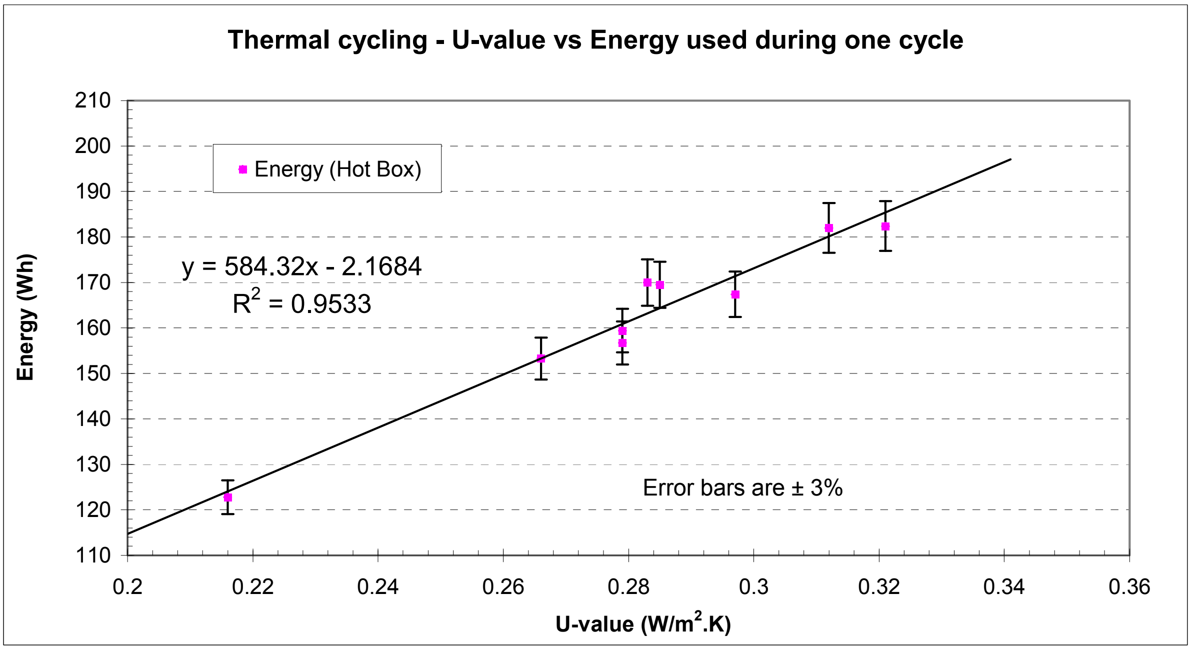
8.2 ENERGY USED PER TEMPERATURE CYCLE

The values of energy (Wh) per oscillation period needed to sustain a constant warm chamber temperature are approximately the same when measured directly from the hot chamber power and by the HFM fixed to the wall surface. The agreement between the values of this parameter by the two measurement methods was very good (see Figure 106). Except for Wall 2, the differences in the Wh values obtained by the different methods range from 1.5% to 9.4%. The exception is the timber frame wall where the HFM was sited directly over the central junction of studs, so the heat flowing through that portion of the wall would be expected to be significantly higher than the whole wall (which it is).

The good agreement between the two methods may be influenced by the fact that the amplitude of the power fluctuations is small compared to the mean power.

The energy required to keep the warm chamber at 24.4 ^{0}C whilst the cold chamber was cycled for one complete cycle (measured in Wh) was plotted against U-value to see if those two properties values were correlated. The quality of the fit shown in Figure 109 would indicate that they are correlated.

Figure 109 U-value vs Energy per cycle



8.3 TIME LAG BETWEEN MAXIMUM TEMPERATURE DIFFERENCE AND MAXIMUM POWER

The lag times between the maximum temperature difference between the hot and cold chambers and the maximum power through the walls are shown in Figure 107. The variation in values that were modelled and measured with the HFM with those derived from the hot box power, for the high mass walls, is quiet marked. The heat flow meter power and VOLTRA derived values seem almost constant at around 10 hours for all the walls except the timber frame wall when the value drops to 7 hours whereas the values derived from the hot box power for walls 1, 4, 6 and 7 are nearly double that value. The reasons for this discrepancy have not been identified. It could be that the methodology described in Section 5.2.1 for deducting the heat transfer through the surround panel is very sensitive the thermal mass of the wall, although these values for Walls 3 and 8 which are fairly high mass are in quiet good agreement. Wall 7, the solid AAC wall, showed a difference in these values less than for the ICF walls but worse than for the Brick walls. The values derived from the hot-box power also are comparable with the values modelled for walls 2 and for wall 3 with no plaster board.

It is interesting to note however that the lag time between the minimum cold surface temperature and the minimum hot surface temperature match more closely the power lag times derived from the hot box power.

To summarise; the values derived from the hot box power show the three ICF wall producing the largest lags. These were about 20 hours as compared to 10 hours for a standard brick/AAC wall. The measurements on walls 3 and 8 were repeated with the plasterboard (and it's associated air cavity) removed. This had either a small or no effect on the lag times. If we take the lag times derived from the HFM power and simulated by Voltra the lag times were all about 10 hours except for the timber frame wall which was lower.

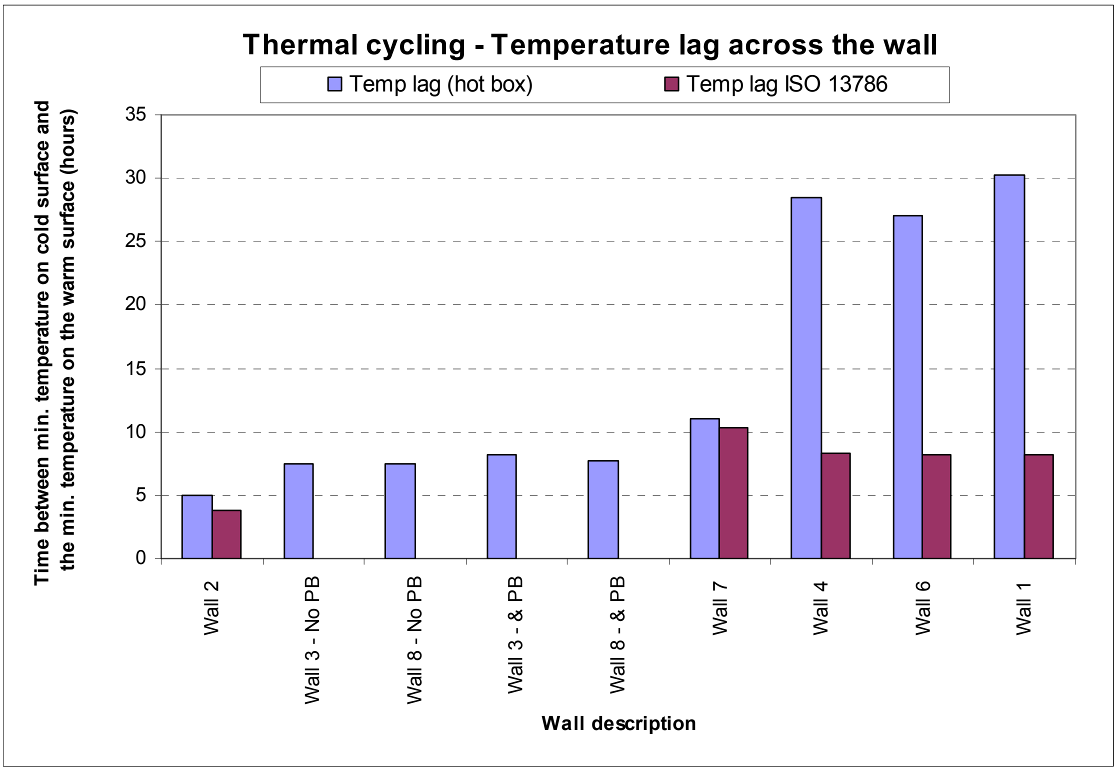
8.4 LAG BETWEEN THE MIN. COLD SIDE TO THE MIN. HOT SIDE TEMPERATURES

This is the time lag between the minimum cold surface temperature and the minimum hot surface temperature. The temperature fluctuations in the hot surface temperature are very small, varying from less than 0.1 °C for the ICF walls to about 0.4 °C for the timber frame wall. This time lag is only a function of the temperature cycling – not the power measurement method and nor was it modelled with VOLTRA. The values measured compared to the decrement time calculated using the procedures specified in ISO 13786 can be seen in Figure 110.

These figures show the ICF walls creating a significantly longer time lag between the external and internal temperatures than the brick/AAC , brick/lightweight concrete and solid AAC walls which in turn created a significantly longer time lag than the timber frame wall.

These results also show that the plasterboard plus associated air cavity had only a very small effect on the two walls that were measured with and without plasterboard – that is walls 3 & Wall 8.

Figure 110 Decrement time lag across walls



8.5 AMPLITUDE OF THE POWER FLUCTUATIONS

This is the amplitude of the variation in power transferred through the test element caused by the temperature cycling of the cold chamber. In percentage terms the agreement between the two sets of values is very poor. The actual power fluctuations for these small area samples (1.44 m^2) are, however, very small. For the six masonry walls the amplitude of those fluctuations only varies from 0.25 W to 0.75 W. This would explain why despite the large the percentage differences in the amplitude of the power fluctuations the agreement in the energy used per cycle was very good. The comparison between the values obtained with the hot-box, HFM and VOLTRA powers can be seen tabulated in Table 21 and in Figure 108.

The amplitude of heat transfer fluctuation is strongly influenced by the thermal mass.

8.6 COMPARISON OF CALCULATED AND MEASURED TEMPERATURE PROFILES.

The results of the temperature profile modelling for walls 3 and 8 show good agreement between the measured and calculated values. The differences between the measured and calculated interface temperatures are shown in Figure 111, Figure 112 and Figure 113 for Wall 3 with plasterboard, Wall 3 without plasterboard and Wall 8 with plasterboard respectively.

Figure 111 Wall 3 with plasterboard - Differences between measured and calculated surface temperatures.

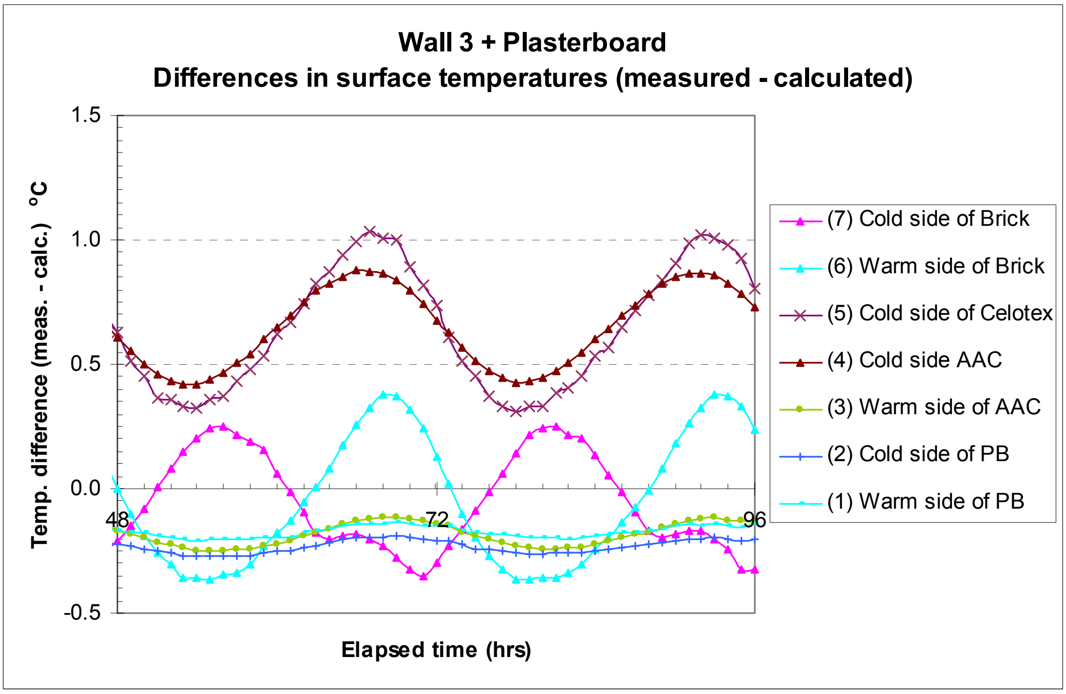


Figure 112 Wall 3 No plasterboard - Differences in measured and calculated surface temperatures

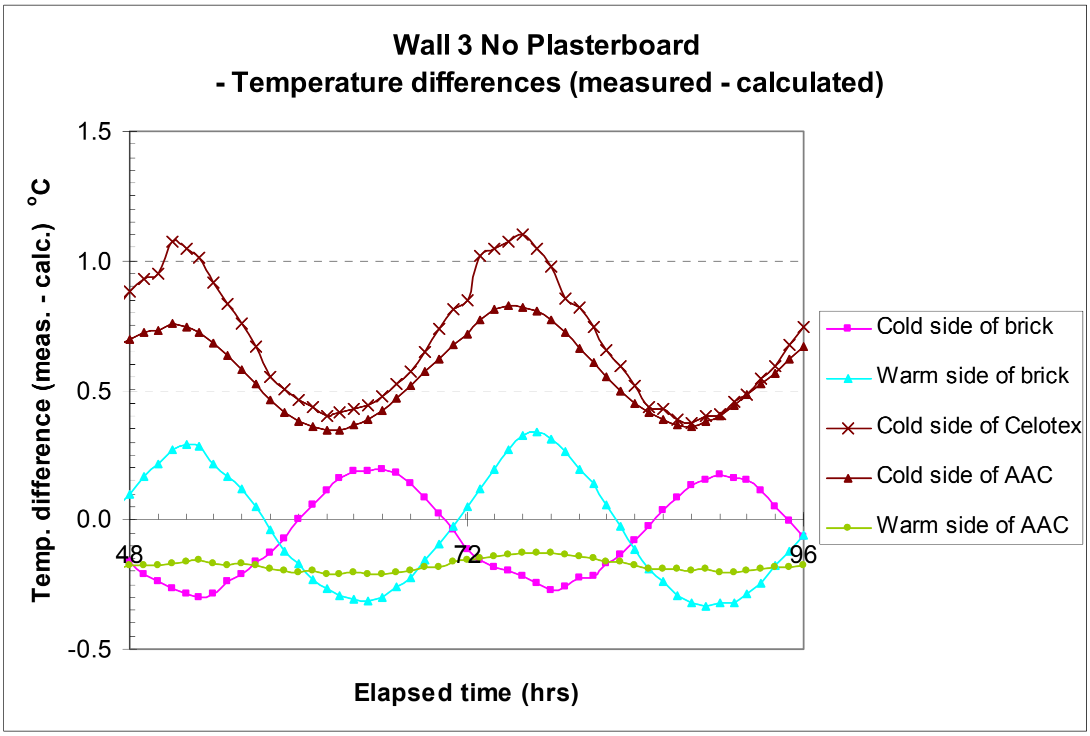
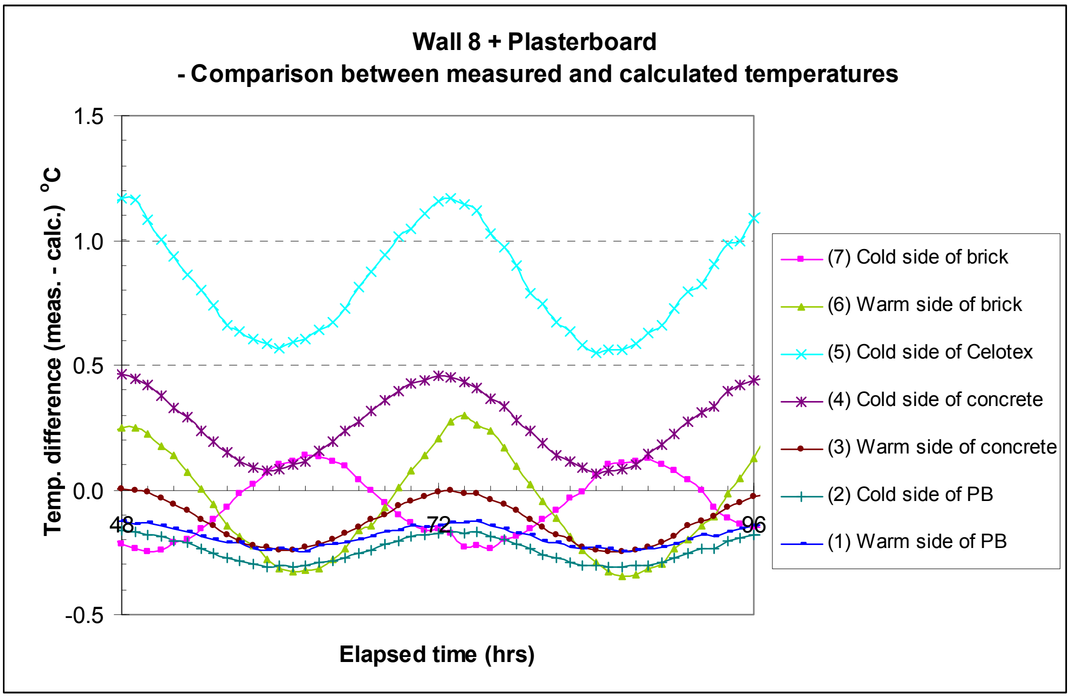


Figure 113 Wall 8 + Plasterboard - Differences in measured and calculated surface temperatures



8.7 COMPARISON BETWEEN MEASURED AND CALCULATED U-VALUES

The steady state U-value of all the walls were measured using the hot-box power as specified in BS EN ISO 8990 and were calculated using the Voltra software. The U-value of Walls 3 and 8 both with and without the plasterboard were also calculated using the methodology specified in BS EN ISO 6946. The Voltra values are compared with the measured values in Table 22 and the BS EN ISO 6946 values are compared with the measured U-values Table 23. They are also shown in graphical form in Figure 114.

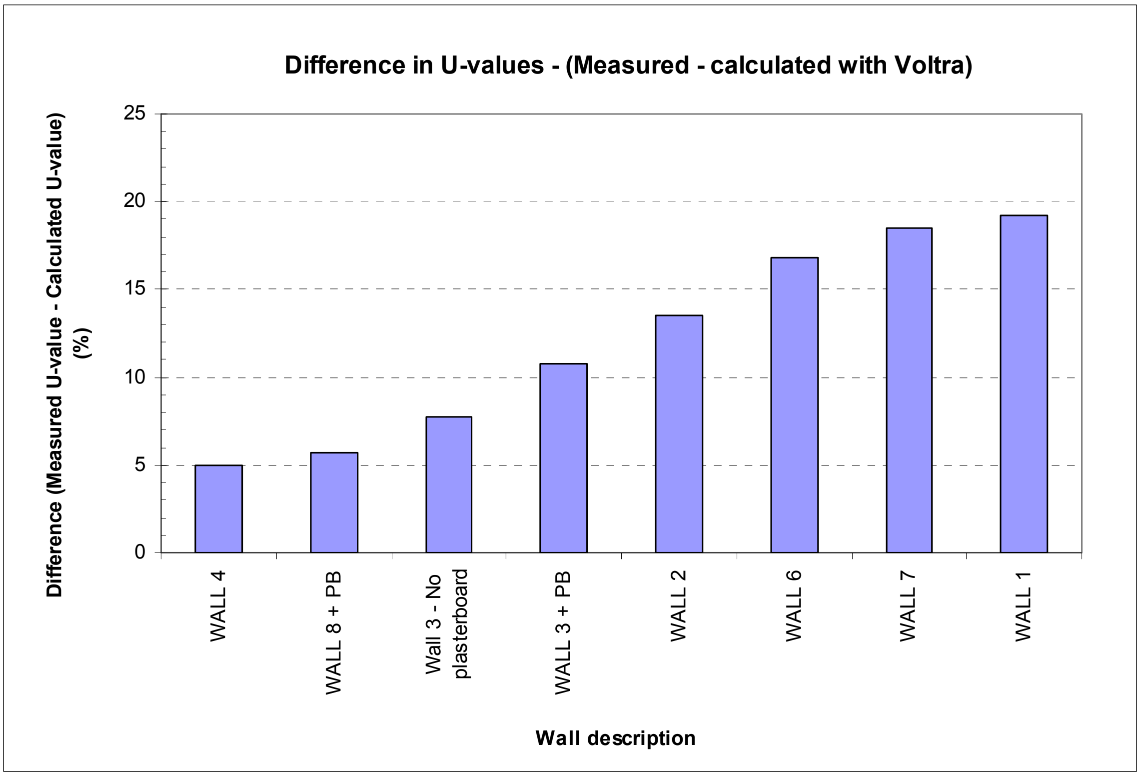
Table 22 Comparison between the measured U-values and those calculated with Voltra

Wall number	U-value - Measured (W/m².K)	U-value Calc. (Voltra) (W/m².K)	% Diff (Meas-Calc)/Meas (%)
WALL 1	0.312	0.252	19
WALL 2	0.266	0.230	14
WALL 3 + PB	0.279	0.249	11
No plasterboard	0.285	0.263	8
WALL 4	0.283	0.269	5
WALL 5	Not built		
WALL 6	0.279	0.232	17
WALL 7	0.216	0.176	19
WALL 8 + PB	0.297	0.28	6
No plasterboard	0.321	no value	

Table 23 Comparison between the measured U-values and those calculated with EN ISO 6946

Wall number	U-value - Measured (W/m².K)	U-value Calculated (EN 6946) (W/m².K)	% Diff (Meas-Calc)/Meas (%)
WALL 3 + PB	0.279	0.268	4
No plasterboard	0.285	0.276	3
WALL 8 + PB	0.297	0.302	-2
No plasterboard	0.321	0.312	3

Figure 114 Comparison between the measured U-values of those calculated with Voltra



There appears no obvious correlation between the difference between the calculated (with Voltra) U-values and the measured values with any other property such as U-value or mass.

The U-values calculated using the procedures specified in EN 6946 are in good agreement with the measured values (see Table 23).

The U-values calculated with Voltra are always lower than those measured.

9 SUMMARY AND CONCLUSIONS

9.1 SUMMARY

a) Steady state U-values

The thermal properties of seven different wall structures were measured directly in the NPL hot box under both steady state thermal cycling conditions. The various properties (that included U-values) that were derived from those measurements can be seen in Table 10. The thermal properties of two of those walls (Wall 3 and Wall 8) were measured both with and without the plasterboard and its associated air cavity to try to identify the effect of the additional thermal resistance that this layer creates on the warm side of the system.

The U-value of all the walls were calculated by Glasgow Caledonian University using Physibel's Voltra software. Those results are also shown in Table 10.

The U-value of two of those walls (Wall 3 and 8) were also calculated following the procedures in EN ISO 6946. Those values are also shown in Table 10.

b) Dynamic measurements and calculations

The dynamic measurements were carried out by holding the warm chamber air temperature constant at 24.6 °C and cycling the cold box air temperature from 2.4 °C to 14.6 °C and back to 2.4 °C in a 24-hour cycle.

The heat flow therefore was always in one direction; from the warm chamber to the cold chamber.

The dynamic measurements were carried out twice, one deriving the power through the walls from the measured hot-box power and the other by measuring the power through the wall by a 250 mm x 250 mm heat flow transducer, fixed to the warm face of the wall.

The dynamic thermal properties of all the walls were also calculated by Glasgow Caledonian University using the Physibel Voltra software (3D transient heat transfer software using rectangular blocks).

The decrement time for walls 1, 2, 4, 6 and 7 were also calculated using the procedures in ISO 13786.

From the measured dynamic data the following properties were derived (see Table 10):

a) Energy (Wh) required maintaining the temperature of the warm chamber air temperature at 24.6 °C over one complete 24 hour cycle (see Figure 106).

b) Time lag between the maximum temperature difference between the cold chamber and warm chamber and the resulting maximum power transfer through the wall.(see Figure 107).

c) Amplitude of the variation in power transfer through the test element caused by the temperature cycling of the cold chamber (see Figure 108).

d) The time lag between the minimum temperature on the cold side and the related minimum temperature on the warm surface (see Figure 110).

The energy used per cycle was measured for each wall using both the hot box power and power through a 250 mm x 250 mm heat flow meter (HFM) and the results are shown in Table 10.

9.2 CONCLUSIONS

i) The agreement between the measured U-values and those calculated with VOLTRA ranged between 5% and 19% with no apparent correlation with any property such as U-value or mass. The measured and calculated U-values are compared in Figure 114. The overall measurement uncertainty of the hot box apparatus for these measurements is estimated to be within ± 6.5 % based on a standard uncertainty multiplied by a coverage factor k = 2, providing a level of confidence of approximately 95 %. The U-values calculated with VOLTRA were always lower than the measured values.

ii) The agreement between the measured U-values and those calculated using the procedures in EN ISO 6946, for walls 3 and 8, was very good, with the maximum variation of 4%

between the measured and calculated values (see Table 23 and in graphical form in Figure 114).

iii) The energy per cycle value correlated well with U-value (see Figure 109) and so was not inversely related to thermal mass.

iv) The temperature of all the interfaces through the walls were measured during the cycling measurements these are shown in Figure 38, Figure 40,Figure 41,Figure 43, Figure 44, Figure 47, Figure 49, Figure 51, Figure 53 and Figure 55. The temperatures of the interfaces for Wall 3 with and without the plasterboard and Wall 8 with the plasterboard were also modelled using Voltra and the agreement was very good (see Figure 111, Figure 112 and Figure 113.)

v) The high mass ICF walls significantly reduced the amplitude of power fluctuations created by the cycling (see Figure 108). Comparing to the standard brick/cavity/PUR/AAC wall 3 with the plasterboard, the ICF walls reduced the amplitude of the power fluctuations by a factor of about 1.8 using the WGHB values and when compared to Wall 3 without plasterboard the reduction in amplitude was a factor of 4.6.

The significant difference between the values of the lag time between the maximum temperature difference and maximum heat flow through the wall for the ICF walls (see Table 21) has not been resolved. On one hand the methodology used to extract this value from the hot-box power data was complex and therefore may be the source of the problem on the other hand the power lag times measured are comparable for the measured temperature lag times. The ratio of temperature lag times to power lag times given in Table 21 show the ICF walls have a ratio of about 1.3 and all the walls but the timber frame wall have a ratio of 0.7. The ratio for the timber frame wall was 1.

There was also a conflict between the value of the time delay between the minimum temperature on the cold side and the minimum temperature on the warm side as measured using the hot box and an equivalent value calculated using the procedures in ISO 13786. The reason for this large discrepancy (for the ICF walls only) must be investigated.

Future measurements

The cycling regime selected did not reproduce the conditions that would make best use of the stored energy in the high mass ICF walls.

Any future measurements should select warm and cold chamber temperature conditions that ensure bidirectional heat flow. This will mean that in a conventional hot box heat flow meters must be used.

It might also be necessary to have a complex temperature regime where the warm (indoor) chamber temperature is lowered periodically to replicate night time set-back where the air temperature in the internal chamber falls below the warm side wall temperature those ensuring heat stored in the wall is transferred into the warm chamber, so reducing the power demand.