

Report

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**Evaluation of the thermal
performance of insulation
systems used in roof
structures**

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Graham Ballard**

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Industry and Innovation Division

ABSTRACT

This report contains the results of a series of U-value measurements on a roof structure insulated with a variety of insulation systems; results of thermal performance measurements carried out using non-steady state temperature conditions and a brief review of the possible methods for determining the thermal performance of insulation systems based on reflective multifoil products.

The thermal transmittance measurements were carried out using the NPL rotatable hot-box facility of a section of roof, insulated with four different insulation systems i) Actis Triso-Super 10 reflective multifoil, ii) Celotex TUFF-R™ rigid polyisocyanurate foam iii) Knauf Rafter Roll 32 glass fibre, iv) and four off, 25 mm deep air cavities with low emittance surfaces. The U-values of the four insulated roof systems were measured at four orientations which were i) the test element mounted vertically with horizontal heat flow, ii) at forty five degrees and iii) horizontally with upward heat flow and iv) mounted horizontally with downward heat flow. The measurement at forty-five degrees was repeated with a small airflow allowed into the air cavity between the tile membrane and the insulation. The U-values measured for these insulated roof structures are in agreement with values that were predicted from classic steady state heat transfer theory, which was demonstrated by calculating the U-value for each roof type using 2D finite element analysis, and air cavity thermal resistance values calculated using the procedures specified in BS ISO 15099.

Temperature cycling measurements were carried out on a low-density glass fibre specimen and an air cavity insulated with Actis Triso-Super 10 reflective multifoil insulation. The energy used per 24 hours (in Watt-hours) obtained from the temperature cycling measurements show the energy required to cycle the low density glass fibre and the air cavity insulated with Actis Triso-Super 10 were within approximately 17% of each other with much of the difference resulting from differences in thermal resistance and the effect of temperature difference on the thermal resistance of air cavities.

A brief review of the various methods of evaluating the thermal performance of reflective multifoil insulation products has also been carried out.

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Approved on behalf of the Managing Director, NPL
by Susan Evans, Director, Industry and Innovation Division

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1 Background

In recent years, controversial claims have been made for the thermal performance of some insulation systems based on the use of low emittance surfaces. The controversy centres around the claims that some of these insulation systems, having an average thickness of 50 mm or less, when fixed in the centre of an air cavity produce an air cavity thermal resistance equivalent to that produced by 200 mm of glass fibre having a thermal conductivity of 0.04 W/m.K; that is equivalent to a thermal resistance of 5 (m².K)/W. Simple calculations indicate that the best thermal resistance that can be achieved with a 50 mm thick insulation material (based on air) and two air cavities is about 3.3 m².K/W and in practice it is likely to be lower than that.

Some of those who have made the measurements on which such claims are based believe that the standard measurement methods such as those carried out using a hot box apparatus, do not measure the heat transfer processes that are occurring in their products. There have also been suggestions that the thermal performance of these products will be enhanced when subjected to non-steady state environmental conditions.

There are a number of factors contributing to the problems associated with the thermal performance of these products. They are:

- The thermal performance of these products is application specific. They rely on increasing the thermal resistance of an air cavity and are not therefore fully characterised by considering simply their own intrinsic properties.
- There are no CEN product standards for these insulation systems.
- Consumers and specifiers often have a poor understanding of the heat transfer principles involved, leaving them unable to make their own judgement.
- Most of the thermal performance values obtained to date are “commercially in confidence”.
- Some organisations have developed “in-house”, comparative measurement procedures using outdoor environments. These methods are not publicly documented, may not be rigorously validated and could be subject to large measurement uncertainties.

This report:

- Summarises the heat transfer processes involved when a structure is insulated with these types of product.
- Gives a brief review of the measurement and calculation standards associated with traditional insulation materials and structures.
- Reviews the various measurement methods available to evaluate these types of products.
- Lists other activities taking place to resolve these issues.
- Describes thermal transmittance measurements made by NPL on representative roof structures insulated with different insulation systems, in a hot-box apparatus.
- Describes power consumption measurements made of low-density glass fibre and an air cavity insulated with Actis Triso-Super 10, in the non-steady state, in a specially adapted guarded heat-flow-meter apparatus.

2 Summary of the heat transfer processes through insulated air cavities

2.1 Steady State heat transfer through an insulated air cavity

2.1.1 The three modes of heat transfer

- Conduction – the heat transfer process through solids
- Convection – heat transfer through fluids (in building situations this is usually air).
- Radiation – heat transfer by electromagnetic radiation emitted from the surface of an object, which is due to the object's temperature. This mode of heat transfer does not require a medium to pass through i.e it can pass through a vacuum.

2.1.2 Definition of steady state

- The external temperatures of the cavity are constant with time.
- The heat energy supplied is used solely to produce the temperature difference across it.
- No heat energy is heating up the materials used to make the structure neither is any being lost in cooling the structure.
- Neither the mass nor specific heat of the insulation and structure are important.

2.1.3 Overview of heat transfer processes in different types of insulation

2.1.3.1 Insulation materials based on trapped air

Materials such as glass fibre or expanded polystyrene (which have thermal conductivity values of around 0.038 W/m.K are considered to be homogenous and work by using a minimum of material to inhibit both heat transfer by convection and by thermal radiation. The material used (e.g. the glass fibres) also creates an additional heat transfer path by allowing thermal conduction through the material itself. In the case of glass fibre, there is an optimum density where the effect on minimising convection and radiation is greater than the increase in heat transfer by thermal conduction through the glass fibres themselves. Reduce the density below that optimum value and the thermal conductivity starts to rise (quite sharply) due to the increased thermal radiation passing through the material. But when the density is increased from this optimum value, however, the thermal conductivity also starts to rise (this time more gradually) due to the increased thermal conduction through the glass fibres.

2.1.3.2 Insulation materials based on trapped high density gases

Although the principle is the same i.e. to reduce convection and radiation by using as little material as possible (for the same reasons as above) – these materials have the advantage of having the expanded polymer foam filled not with air but with blowing gases such as hydrofluorocarbons (HFCs) or hydrochlorofluorocarbons (HCFCs) which have a lower thermal conductivity than air. This means that some of these materials can have a lower thermal conductivity than air, values of 0.018 W/m.K are possible - but have to be clad in some way to stop those gases diffusing out of the polymer matrix. The producer must quote a 25 year design value based on accelerated aging measurements.

2.1.3.3 Insulation utilising low emittance surfaces

Using low emittance surfaces to reduce radiant heat exchange is a well-established technique (Sir James Dewar famously used silver to enhance the performance of his famous vacuum

flask in 1882). Some manufacturers of materials such as polyurethane and glass fibre supply products with a low emittance outer layer. The product that is of special interest for this report, however, is the one that comprises a number of layers of low density wadding between thin membranes with low emittance surfaces. The outer membranes of such products are usually of rather more robust materials but again with low emittance surfaces. The low density wadding is there to inhibit convection of the air between the membranes, again using the minimum of material which again provides an additional heat transfer path by thermal conduction. The density can be lower than for uncovered material because the low emittance membranes serve to reduce the thermal radiation through the wadding. With conventional wadding material, the thermal resistance between each layer cannot be less than for still air. The outer, low emittance surfaces have to be taken advantage of by ensuring the product is installed in such a way as to create an air cavity in front of each outer surface. The low emittance surface acts to increase the thermal resistance of those unventilated air cavities exactly as low emittance coating such as Pilkington K, does in a double glazed window unit. The use of low emittance surfaces to improve thermal insulation is a well-established technique and has been used for decades in many different applications. The vacuum flask has already been mentioned but other examples are for cryogenic insulation where the gaps between the reflective layers are usually evacuated and at high temperatures where the Stefan's Law relationship between radiant energy and the forth power of the absolute temperature makes concentric "reflective radiation shields" common practice.

2.1.3.4 Insulation utilising air at reduced pressure

A vacuum is an extremely efficient insulator because it totally excludes conduction and / or convection through the gas (steps have to be taken to reduce radiant exchange of course).. The relationship between gas pressure and thermal conductivity is, however, such that to achieve thermal conductivity values about 0.001 W/m.K (compare with 0.025 W/m.K for air at atmospheric pressure) the gas pressure must be below about 0.001 mbar, very difficult to achieve and sustain over long periods of time. If, however, the gas space is filled with particles whose diameter is similar to the means free path of the gas molecules then thermal conductivity values of around 0.005 W/m.K can be achieved with gas pressures of about 1 mbar to 10 mbar.

2.1.3.5 Insulation only using particle size and radiation blocking

Some materials utilise the above effect without any reduction in gas pressure at all. These are often some type of Aerogel material whose pore diameters are closely matched to the mean free path of the air. These can achieve thermal conductivity values of around 0.014 W/m.K

2.1.4 Heat transfer through air cavities

The thermal performance of an unventilated air cavity is well understood – it depends on:-

- Cavity depth
- Cavity aspect ratio (height to depth)
- Total hemispherical emissivity of the bounding surfaces
- Temperature difference across the cavity
- Orientation with respect to gravity.
- Gas type (but for most building applications it is air).

The glazing industry routinely calculates the thermal resistance of air (or even gas filled) cavities using the procedures in BS EN 673 or BS ISO 15099. A simple procedure for calculating the thermal resistance of an air cavity bounded by one low emittance surface and one high emittance surface is given in BS EN ISO 6946 and tables of air cavity thermal values for different temperature differences and different emittance are given in the ASHRAE Book of Fundamentals.

The effects of orientation, temperature difference, emittance and cavity depth can be seen by looking at the air cavity thermal resistance values given in Table 1 (effect of temperature difference and emittance), Table 2 (effect of cavity depth) and Table 3 (effect of orientation). All these values were calculated using the procedures specified in BS ISO 15099.

It can be seen from the values in those tables that the thermal performance of any structure insulated with one or more air cavities will depend on all these parameters.

Table 1 Effect of temperature difference and emittance on cavity thermal resistance

Cavity thermal resistances calculated using procedures given in BS ISO 15099				
* Cavity at 45 degrees - heat flow up. * Cavity depth is 25 mm * Cavity mean temperature = 10 °C * One side of the cavity has an emittance of 0.9				
	The other surface $\epsilon = 0.05$	The other surface $\epsilon = 0.1$	The other surface $\epsilon = 0.2$	The other surface $\epsilon = 0.4$
Temperature difference (°C)	Gas space thermal resistance (m ² .K/W)	Gas space thermal resistance (m ² .K/W)	Gas space thermal resistance (m ² .K/W)	Gas space thermal resistance (m ² .K/W)
30	0.284	0.414	0.341	0.262
20	0.311			
16	0.327			
14	0.338			
12	0.351			
10	0.369			
9	0.380			
8	0.394			
7	0.411			
6	0.434			
5	0.466			
4	0.508			
3	0.563			
2	0.671			

Table 2 Effect of cavity depth on air cavity thermal resistance

ISO 15099 45 degree cavity - heat up - $\epsilon_1 = 0.9$ & $\epsilon_2 = 0.1$ @ Mean temp = 10 °C & Temperature difference = 5 °C					
Cavity depth (mms)	12	25	50	75	100
Gas space thermal resistance ($\text{m}^2 \cdot \text{K/W}$)	0.377	0.414	0.436	0.479	0.506

Table 3 Effect of orientation on air cavity thermal resistance

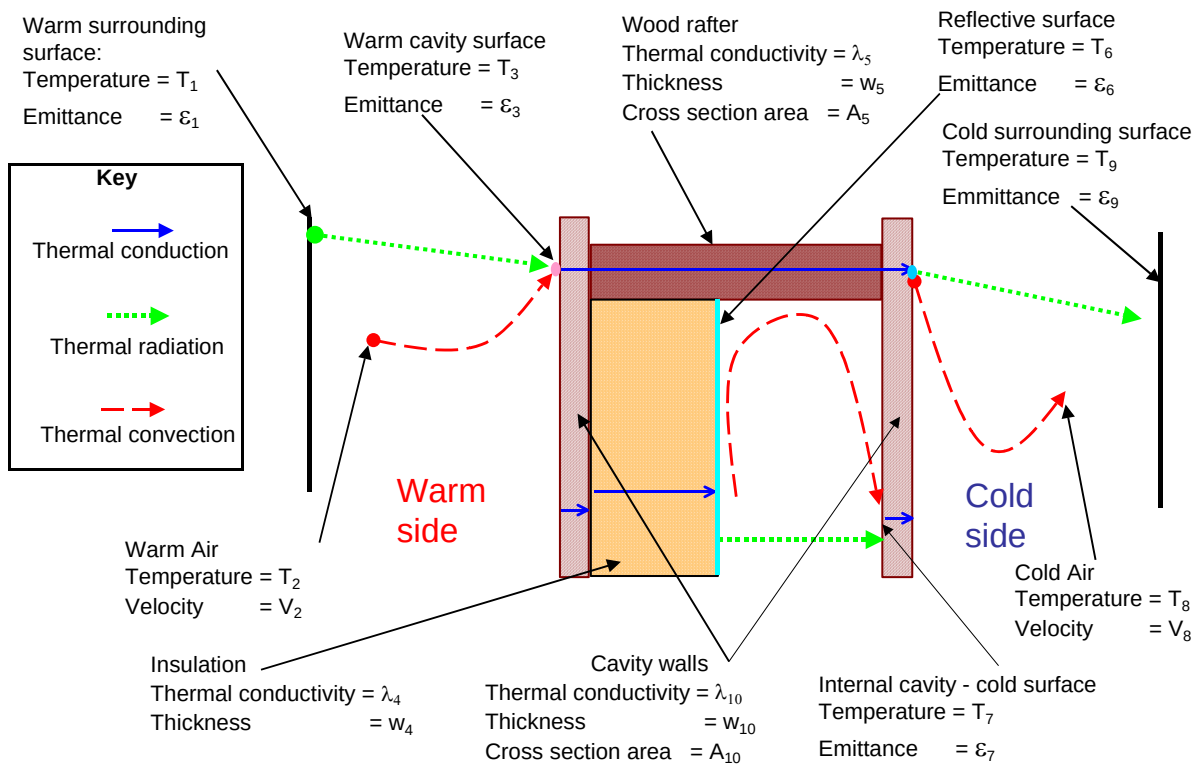
ISO 15099 - $\epsilon_1 = 0.9$ & $\epsilon_2 = 0.1$ @ Mean temp = 10 °C & Temperature difference = 5 °C & Cavity depth 50 mms					
Heat flow direction					
Gas space thermal resistance ($\text{m}^2 \cdot \text{K/W}$)	0.505	0.436	0.408	0.932	

2.1.5 Heat transfer processes across an insulated cavity having cold bridges

The various heat transfer processes that take place across an insulated air cavity, with cold bridges, are listed below and shown in Figure 1 – which also shows the important parameters for each of the modes of heat transfer.

- From the warm environment into the structure.
- Through the walls of the cavity by conduction – (Note: When the air cavity thermal resistance has been measured at NPL, the surface temperature of the *inside* face of the air cavity has been used and so the thermal resistance of the cavity walls are excluded).
- Across the warm side air cavity (see details below)
- Through any bridging structure (eg rafters)
- Through the insulation material (see description above)
- Across the cold side air cavity (see details below)
- Through any bridging structure (eg rafters)
- Through the walls of the cavity by conduction
- From the cavity wall to cold environment

Figure 1 Heat transfer processes through insulated air cavity showing the important parameters.



2.2 Non steady state thermal properties

The thermal performance of insulation systems in non-steady state conditions (where one or more of the boundary temperatures change with time) is specific to the application and the nature of the non-steady state conditions to which the application is subjected. Under these conditions, the simple equations used to calculate steady state heat transfer no longer apply.

The usual procedure for components used in buildings is to measure the steady state properties of the materials (in a hot plate apparatus) or of complete sub-sections (in a hot box apparatus) using standard apparatus and procedures and then use that data to calculate the non-steady state performance of the whole building over a defined period of time (day, week, month or year) when it is subjected to a particular set of weather conditions.

The direct measurement of overall thermal performance of building components in a real, non-steady state environment is difficult and up to now has rarely been attempted. Facilities have been built to measure the thermal performance of glazed products by measuring the net heat flow through them, when exposed to the real environment, so enabling the complex effects of the solar gain at different angles throughout a day and over many months to be determined. The best example of such a facility is at EMPA in Switzerland. It is a complex and very expensive facility that is mainly used for research.

3 Review of methods of evaluating the thermal performance of multifoil insulation systems.

3.1 Measure thermal resistance and emittance and calculate air cavity resistance

Currently a European Technical Approval (ETA) is being produced for these products. An ETS is produced when no harmonized European specification for the product exists. In that case the European Organisation for Technical Approvals (EOTA) and its approval bodies can issue a ETA, which will allow the product to be sold with the CE marking in the European Economic Area. ETAs are based on a Common Understanding of Assessment Procedures (CUAP) for specific products. The CUAP being produced utilises the following method of determining the thermal performance of these products:

- i) Measure the thermal resistance of the product in a hot-plate apparatus
- ii) Measure the total emittance of the external surfaces.
- iii) Calculate the thermal performance of any structure it was used to insulate.

This method suffers from two problems.

- 1) Many of the reflective multifoil products do not have a uniform shape, some are in fact “quilted” and so measuring their thermal resistance accurately in a hot plate apparatus is difficult. This difficulty is increased by the low emittance external surfaces that will have an effect on the small air cavities that are created between the external surfaces of the product and the hot and cold plates of the apparatus. In the CUAP method, an attempt is made to account for this additional thermal resistance by spraying the product matt black and re-measuring it. Then, assuming the air cavities created are the same for both measurements, the thermal resistance of the external air cavities is estimated and deducted from the overall thermal resistance value.
- 2) Measuring the emittance of the external surfaces is difficult. There are no standards for making emittance measurements of these types of surface and very few institutes are involved in carrying them out. The rigorous method of making emittance measurements is expensive and requires a very flat surface. There is one very simple device for measuring emittance covered by ASTM C1371, but there is only one manufacturer of this device and it has never been independently validated. It is repeatable but the absolute measurement uncertainty of the technique is not known. It can only be used on material with high thermal conductivity, so it cannot be used on made-up insulation products. The emittance of many plastic coated, aluminium materials must be measured after fabrication because the heating involved in manufacture can alter the emittance of the surface because of the effect on the plastic coating.

3.2 Measure thermal resistance of air cavity in hot box apparatus

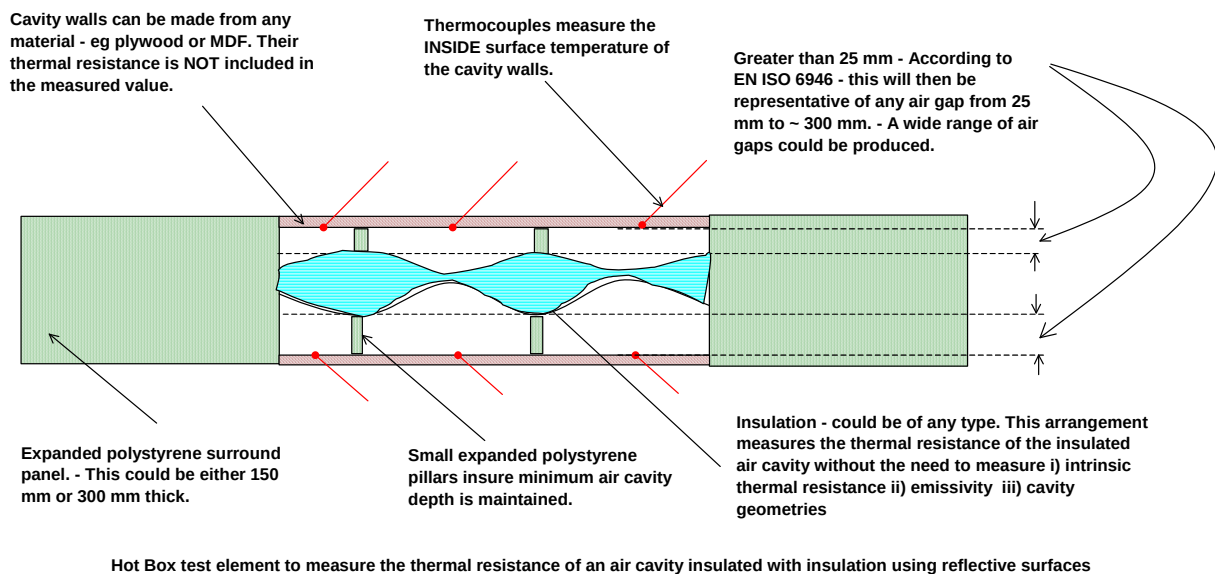
The product under investigation is mounted in the centre of an unventilated air cavity, typically 2 m long by 1 m wide and is kept in position by a number of small, expanded polystyrene pillars (Figure 2). The temperature of the inside surfaces of the cavity are measured by nine thermocouples on each surface. The power through the system is measured and the thermal resistance of the insulated cavity measured. This has a number of advantages over the method described in section 3.1. These are:-

- No need to measure emittance of the two external surfaces
- No need to measure intrinsic thermal resistance

- Irregular shaped products do not pose a problem
- Thermal effects of overlaps used in practice can be accounted for.
- Real convective effects are measured – ie not reliant on calculations using simplified convection correlations.
- It can be measured at whatever orientation is appropriate.

The thermal resistance values produced can then be used in a variety of calculation procedures to determine the U-value of the actual application.

Figure 2 Test element used to measure the thermal resistance of an air cavity in a hot box



3.3 Measure the thermal transmittance of a representative structure in a hot box.

In this method a representative section of actual roof (or wall or floor) structure is made insulated with the target product and its U-value measured in the appropriate orientation. Sections up to 2 m x 2 m can be measured in the NPL rotatable hot box, but usually specimens approximately 1.5 m x 1.25 m are used. This was the procedure adopted for the measurements made for this project. A typical insulated roof structure is shown in Figure 3. This value includes all the effects of the cold bridging due to the rafters.

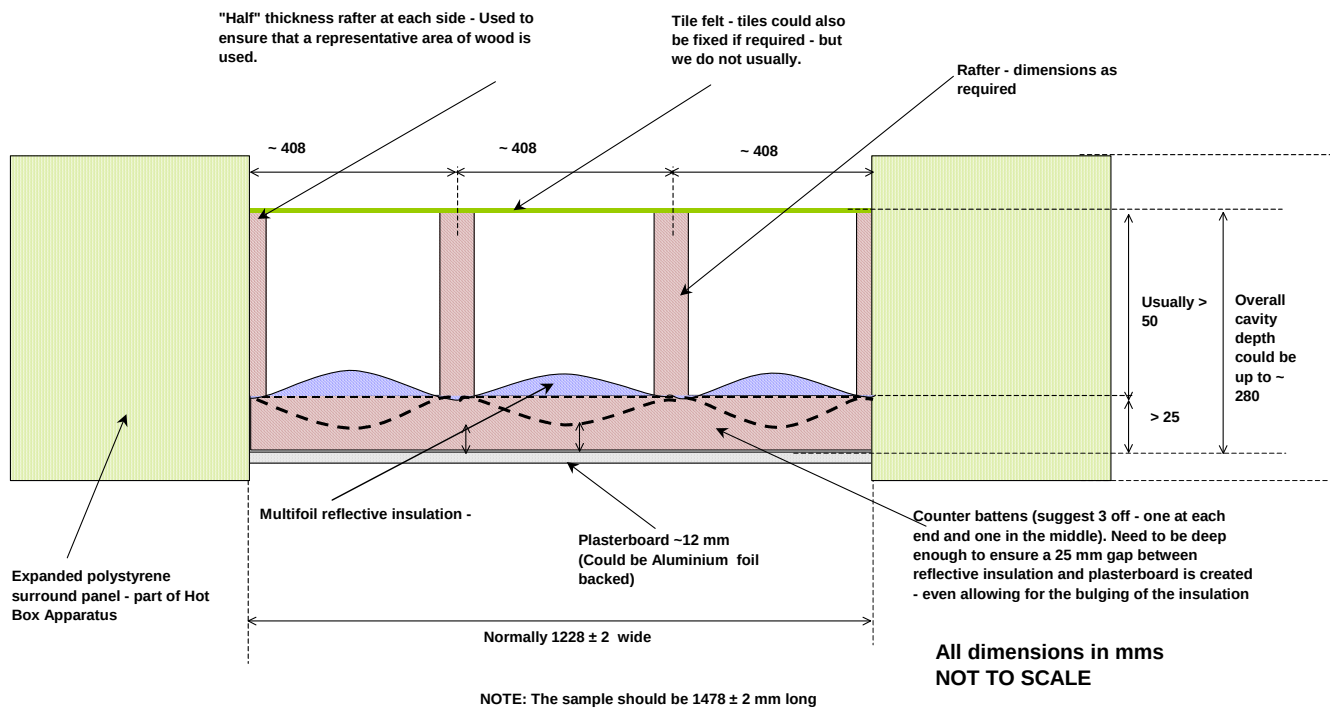
Advantages of this method;

- Output directly gives U-value data for a specific structure – no calculations needed.
- It will give a value very near the actual U-value of the actual roof.

Disadvantage of the method:

- A separate test is needed for each structure

Figure 3 Typical representative roof structure test element



3.4 Measurement apparatus utilising the real outdoor environment.

This is a test cell with the specimen exposed to the real climate. The difficulties in carrying out accurate measurements and extracting the thermal performance values for individual components of a structure increase dramatically when real climatic conditions are used. The varying effects of wind, rain, solar gain and fluctuating air temperature make interpreting the measured data very difficult. There have been a number of attempts to do this. The EU PASSYS Programme and the EMPA Solar Heat Gain facility are good examples.

Advantages:

- Controlled and monitored interior environment; monitored exterior environment.
- Performance measured will include solar gain.
- Performance will include thermal inertia effects.
- It is an absolute method

Disadvantages

- Very difficult to extract "standard" thermal performance data from the results as it requires complex mathematics^[1].

3.5 Compare products installed in identical “simple buildings” exposed to real environment.

This is the method used by most institutes that have produced the controversial thermal performance values for reflective insulation products. The important issues when carrying out these types of measurement are:-

- i. Carry out a sensitivity analysis of the system. For example what percentage of the total energy used goes through the floor and the cold bridging rafters. What percentage of the measured energy goes into heating up the structure? Is the measurement method sensitive enough to detect differences between the two samples being compared?
- ii. Ensure both simple building are the same thermally (carry out measurements of the buildings in a non-insulated state in the same types of weather conditions that will be used to compare the products.
- iii. Ensure the reference material is well characterised and installed as perfectly as possible and in a manner required by the manufacturer of that product.
- iv. Validate the whole system by measuring another reference material in the “other” building. For example if 100 mm thick expanded polystyrene was used as the reference material in building 1 use 50 mm of the same expanded polystyrene in building 2.
- v. Measure the air infiltration rates for the buildings with both the reference material and the target material. Then calculate what effect air infiltration that is having on the measured energy used. It should be remembered that the energy used to keep these well insulated buildings (U-value of the whole building approximately $0.2 \text{ W/m}^2\cdot\text{K}$ which is much lower than for a “normal” building) at a normal indoor temperature of say 25°C , will be quite low and therefore the energy used to warm the infiltrating cold air will be a significant percentage of the total.

Advantages

- i. Will take into account the effects of installing materials in an almost real situation e.g. how such features as joins and overlaps are dealt with.

Disadvantages

- i. Very difficult to extract steady state thermal performance data for the insulation from the measured data.
- ii. Results specific to that structure and cannot be extrapolated to other structures.
- iii. Results specific to the weather conditions present during that test.
- iv. Low measurement sensitivity due to large and un-quantified heat transfer associated with changing the temperature of the “building” structure, heat transfer through the “cold bridging” of the rafters and through the large area of floor.

3.6 Insulate a “real building” and monitor energy use

This would mainly be used to check the whole building energy calculation not the performance of one part of the structure. It would be very difficult to determine the thermal performance of one component of the building from such measurements.

4 CEN activities related to thermal performance of reflective insulation

Below is a list of current CEN activities related to resolving these measurement problems.

- i. Common Understanding of Assessment Procedure (CUAP)
Contact: CSTB, 84, avenue Jean Jaurès, Champs-sur-Marne,
77447 Marne-la-Vallée cedex 2, France
- ii. CEN TC89 WG12 – Standardisation of the assessment of the thermal performance of products based upon or utilising reflective or low emittance layers.
Contact: Carol Houghton, CJHconsult Associates [carol@cjhconsult-associates.co.uk]
- iii. CEN Workshop - Evaluation of Thin Multilayer Reflective Insulation Products by *in situ* Testing.
Contact: CEN Management Centre, Ms Gaïd Le Gall, Programme manager,
Workshops, CEN European Committee for Standardization.
[gaid.legall@cen.eu]

5 Hot box measurements carried out at NPL

5.1 Description of the NPL hot box and measurement procedures

The NPL thermal transmittance facility comprises two hot-box apparatus accredited to by UKAS to carry out measurements to EN ISO 8990, EN ISO 12567-1 and EN ISO 12567-2. The UKAS accreditation is to the EN ISO 17025 accreditation standard. The rotatable hot-box used to carry out the measurements reported in Section 5.3 is capable of carrying out measurements with the test element positioned in any position from horizontal with vertically up heat flow through to horizontal with vertically down heat flow (important when the sample includes air cavities).

A side elevation, cross sectional sketch of the two chambers comprising the hot-box apparatus is shown in Figure 4. The hot-box apparatus is designed to measure the total heat transfer through large, non-homogeneous structures, where the heat transfer into and out of the specimen involves both convective and radiant heat transfer and the heat transfer through the specimen can involve any combination of conduction, convection and radiation. The design and operation of the hot-box apparatus are specified in EN ISO 8990 and EN 1946 Part 4 and the details of the validation measurements are given in NPL Report CBTLM 25 “Validation of the NPL rotatable wall guarded hot box with horizontal heat flow” and NPL Report DEPC-TH-002 “An investigation of measurement procedures needed to determine thermal transmittance of deep structures using both horizontal and vertical heat flow”.

The apparatus comprises a hot chamber and a cold chamber. The specimen is fixed between the two chambers, mounted in a surround panel made from insulation material of known thermal properties. Both chambers are designed to enable the following:-

- Air movement:
 - Produced
 - Controlled
 - Measured

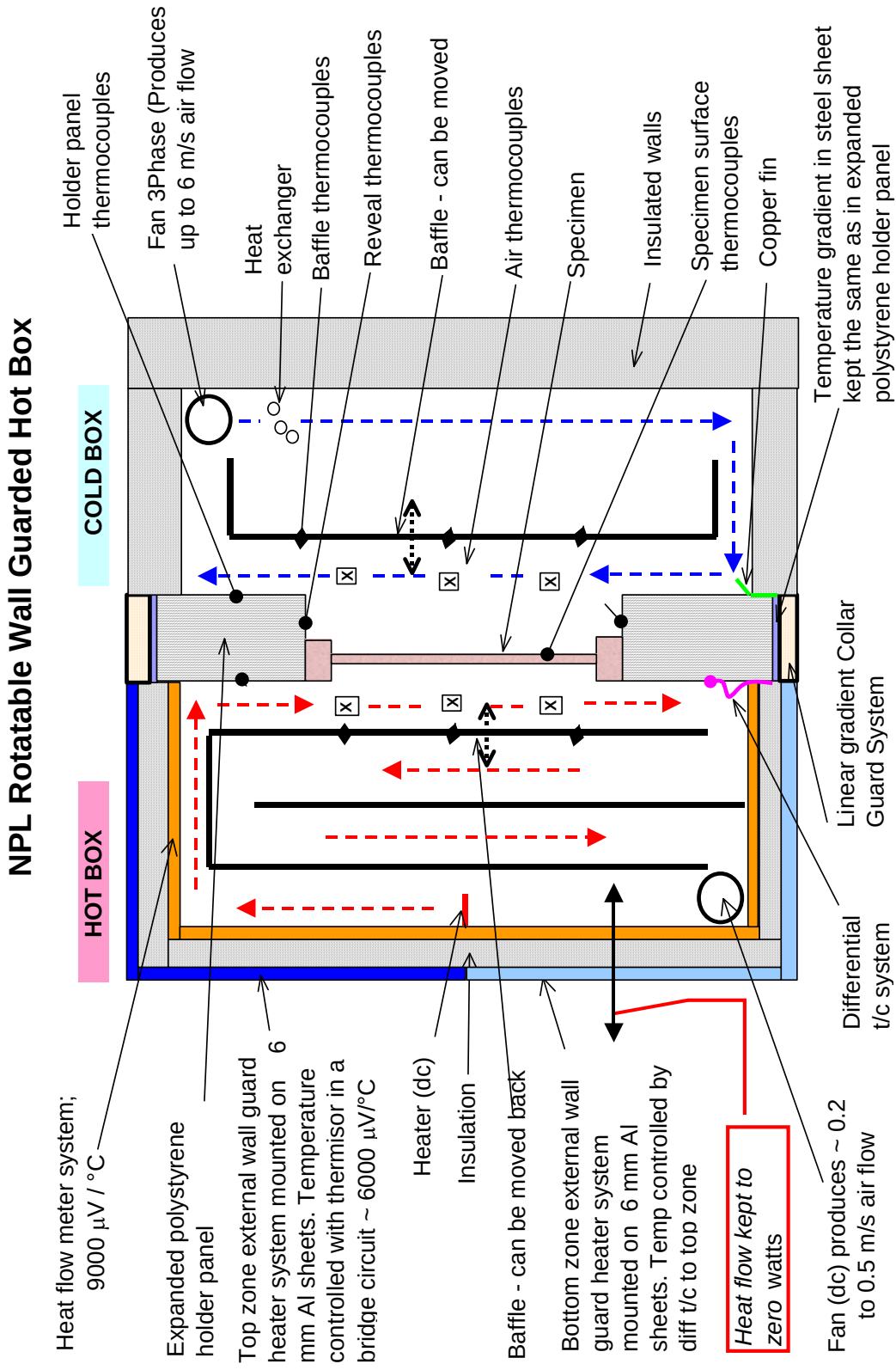
- These temperatures to be measured:
 - Air
 - Surface of the surround panel
 - Specimen surface
 - Surfaces radiating to the specimen
- Most importantly and the most difficult to achieve - the hot chamber of the apparatus is designed and built to ensure that ALL the measured power produced in the hot chamber, to maintain a temperature difference across the specimen, actually goes through the specimen and surround panel. It is important that there is no significant heat flow out of or into the hot chamber, other than through the specimen and surround panel.
- The total power used in the hot chamber is accurately measured.
- The air temperature in the cold chamber is kept at a constant low temperature throughout (often about 2 °C) the measurement, by a suitable chiller system

The NPL rotatable hot-box can carry out U-value measurements with the test specimen in any orientation; from vertical through to horizontal with the cold box above the hot- box or horizontal with the hot-chamber above the cold chamber.

The overall measurement uncertainty of the U-value measurements made of these types of structures, with this apparatus, is estimated to be within $\pm 7.2\%$ based on a standard uncertainty multiplied by a coverage factor $k = 2$, providing a level of confidence of approximately 95 %.

The repeatability of the apparatus when measuring these types of structures has been determined to be within $\pm 2\%$

Figure 4 Schematic diagram of Rotatable Hot Box



5.2 Results of previous hot box measurements of reflective insulation products.

5.2.1 Measurements of simple air cavity resistance

NPL has carried out twenty thermal resistance measurements of air cavities insulated with reflective insulation. These have included test elements comprising one and two air cavities; different cavity depths and measurements at different orientations. The range of total thermal resistance values measured is from $0.55 \text{ m}^2\cdot\text{K/W}$ to $2 \text{ m}^2\cdot\text{K/W}$. The relationship between air cavity thermal resistance and its orientation for one and two cavities specimens (for one material) can be seen in Figure 5 and the variation of thermal resistance with cavity depth can be seen in Figure 6.

Figure 5 Historic values:- Thermal resistances of air cavity vs orientation.

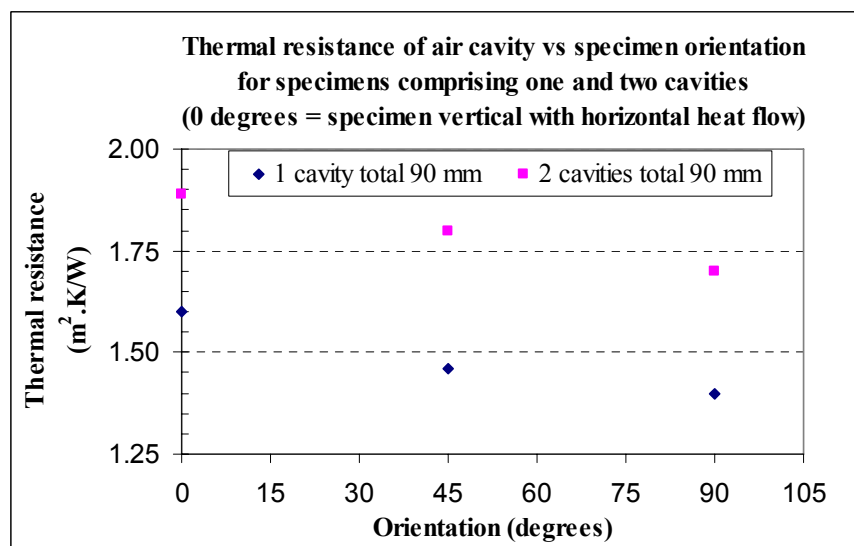
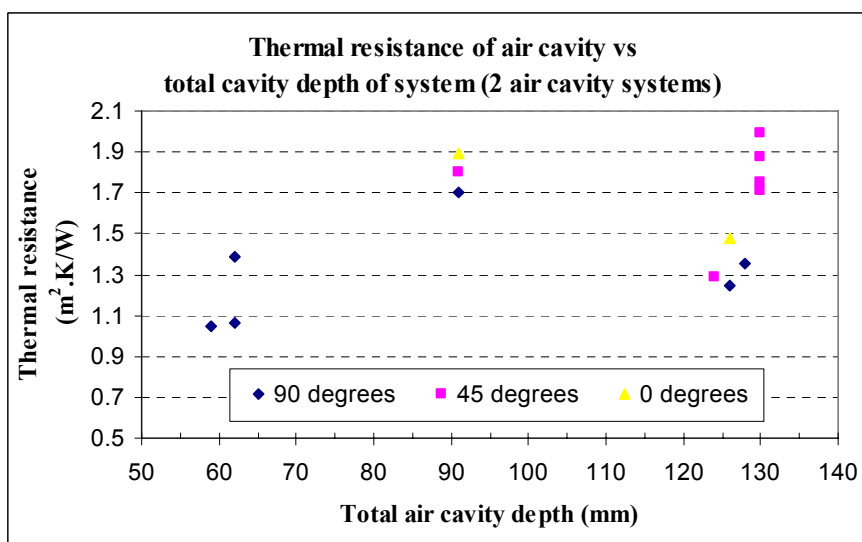


Figure 6 Historic air cavity values:- Thermal resistance vs air cavity depth.



5.2.2 Representative roof structures

A wide variety of roof structures have been measured at NPL and it is therefore difficult to draw simple conclusions from the results. They have all been of roofs with two full rafters and two half rafters (for explanation see section 5.3.1), insulation, plaster board and “tile felt”. Some have had more than one layer of reflective insulation. The measured U-values for those systems ranged from 0.3 W/(m².K) to 0.86 W/(m².K).

5.3 Hot box measurements of insulated roofs carried out for this project

5.3.1 Description of insulated roof structures that were tested

The basic roof structure (see for example Figure 8 and Figure 9) comprised:

Size	1.48m long x 1.23m wide
Rafters	2 off 38mm wide wood rafters at 409mm centres and two off 19mm wide “half” rafters down the sides of the structure. These half rafters ensured that the cross section area of rafters is representative of the whole structure. In essence the adiabatic cut lines you would use in a numerical model, bound the test element.
Insulation	Fixed as appropriate (see individual sketches).
Warm side	A 12.5mm thick, aluminium foil-backed, plasterboard sheet was fixed either to the counter-battens or the rafters as appropriate.
Cold side	A roofing membrane, Lafarge Veltitech 180 was fixed to the cold end of the rafters creating a further air cavity between insulation and the membrane. This “cold side air cavity” was 50 mm deep for the traditional insulation and the special “layers of air cavities” insulation and approximately 100 mm deep with the Actis Triso-Super 10 insulation
External air vent	To investigate effect of air movement in the “cold side air cavity”, a perforated metal strip was fixed near the top and bottom of the membrane. The strip was taped over for the non-vented measurements and removed when air infiltration was required. The exposed, perforated metal strip was 25 mm wide with small (1.2 mm diameter) holes producing 42% of open area. The position of this strip is shown in Figure 7.
Overall thickness of test element	162 mm

Four different insulation systems were measured.

- i. Actis Triso-Super 10 – see Figure 8
- ii. Celotex TUFF-R™ GA 3050
rigid polyisocyanurate foam ($\lambda = 0.023 \text{ W/m.K}$) – see Figure 9
- iii. Glass fibre Knauf Rafter Roll 32
($\lambda = 0.032 \text{ W/m.K}$) – see Figure 10
- iv. Reflective air cavities formed by 2 mm cardboard,
covered on both sides with aluminium foil. – see Figure 11

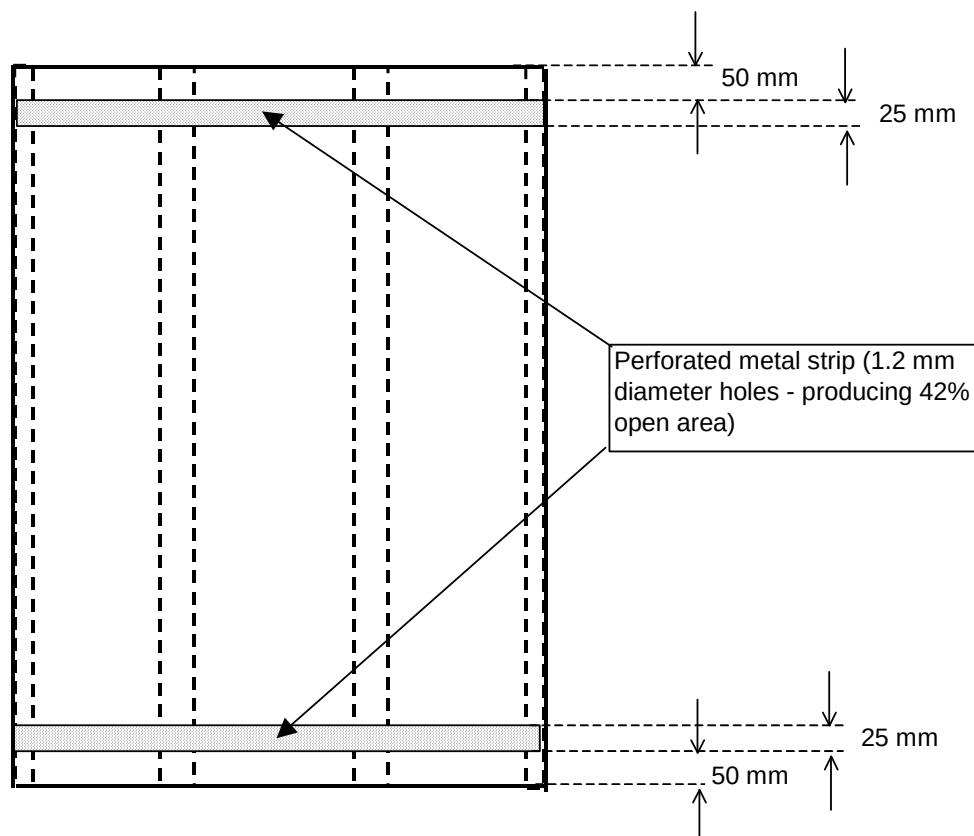


Figure 7 Position of perforated metal strip

5.3.2 Results of the thermal transmittance measurements

A set of typical measured values used to derive the U-value from the measurements can be seen in Table 4. The measured U-values of all the test elements that are described in Section 5.3.1, in the different orientations, can be seen in Table 5.

Figure 8 Cross section sketch of test element insulated with Triso-Super 10

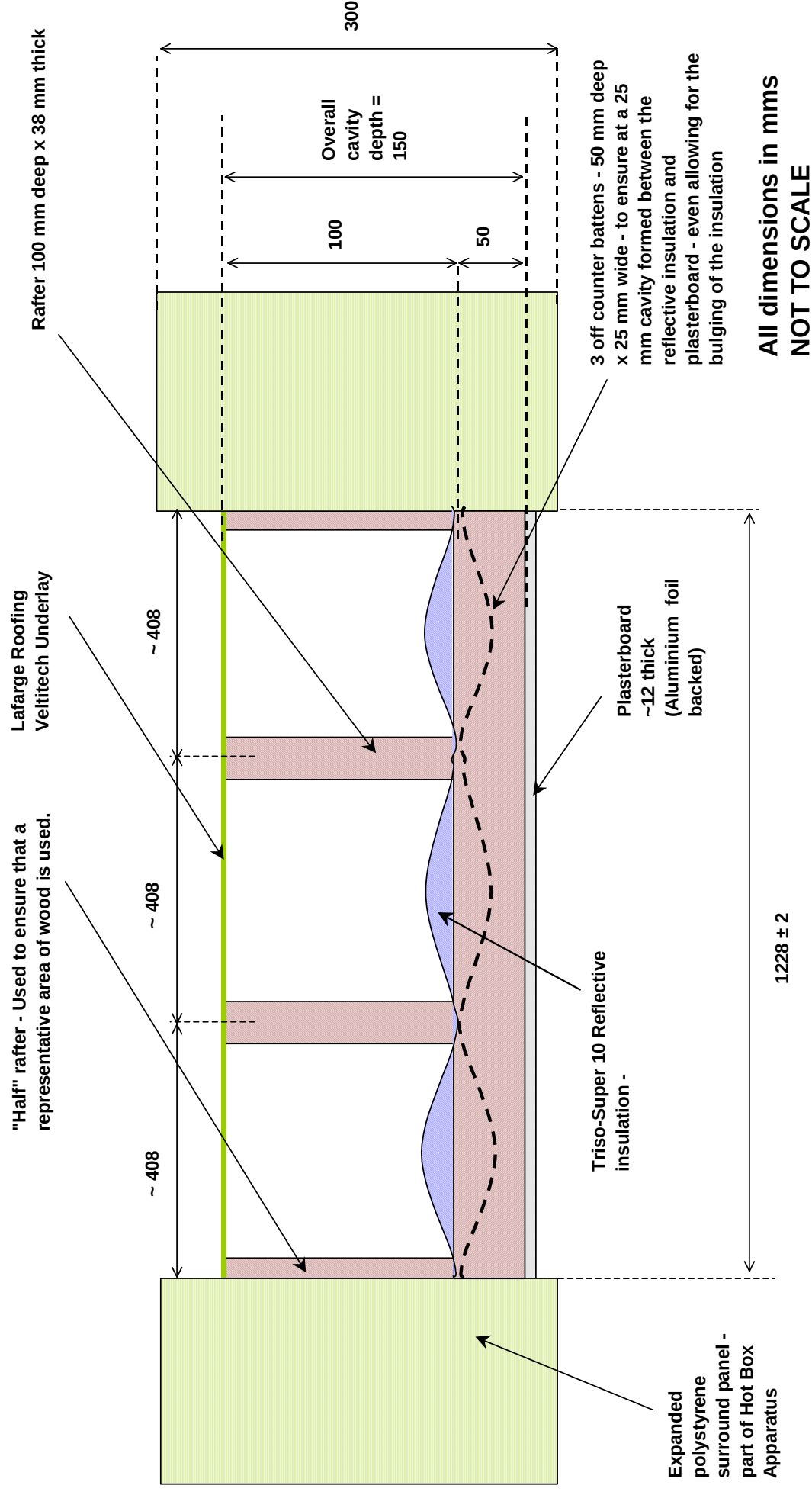


Figure 9 Cross section sketch of test element insulated with Celotex TUFF-R™ GA 3050 rigid polyisocyanurate foam

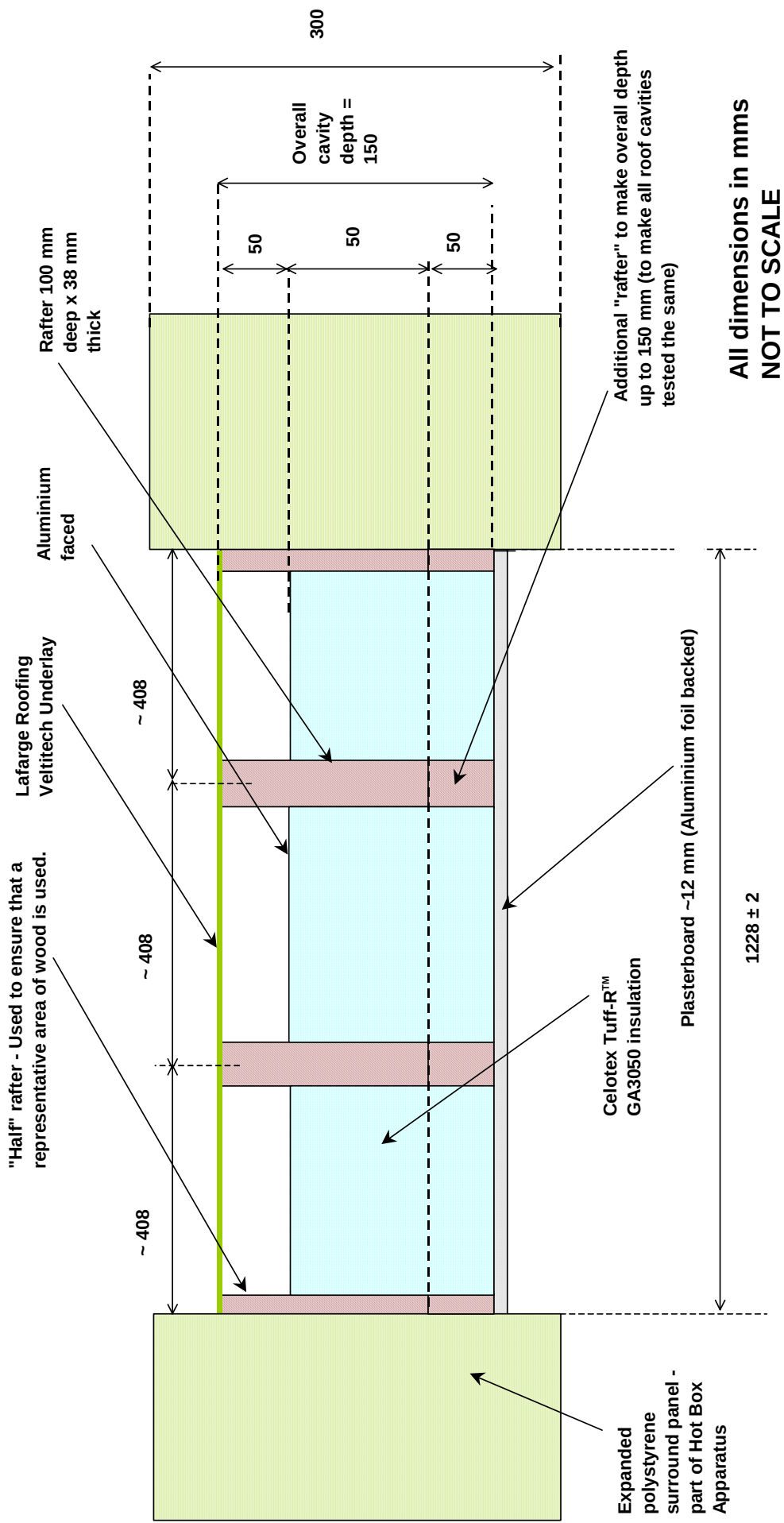
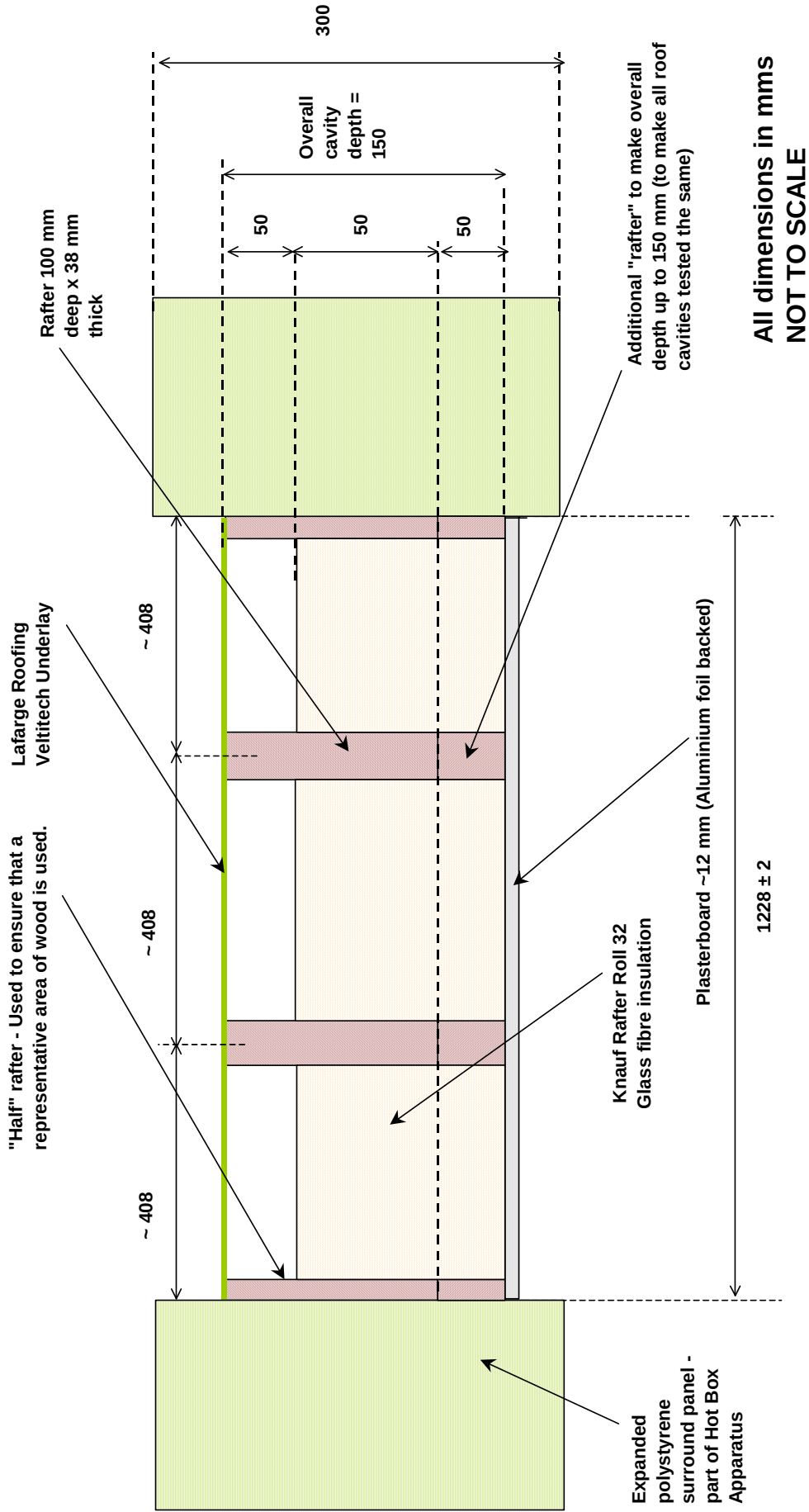
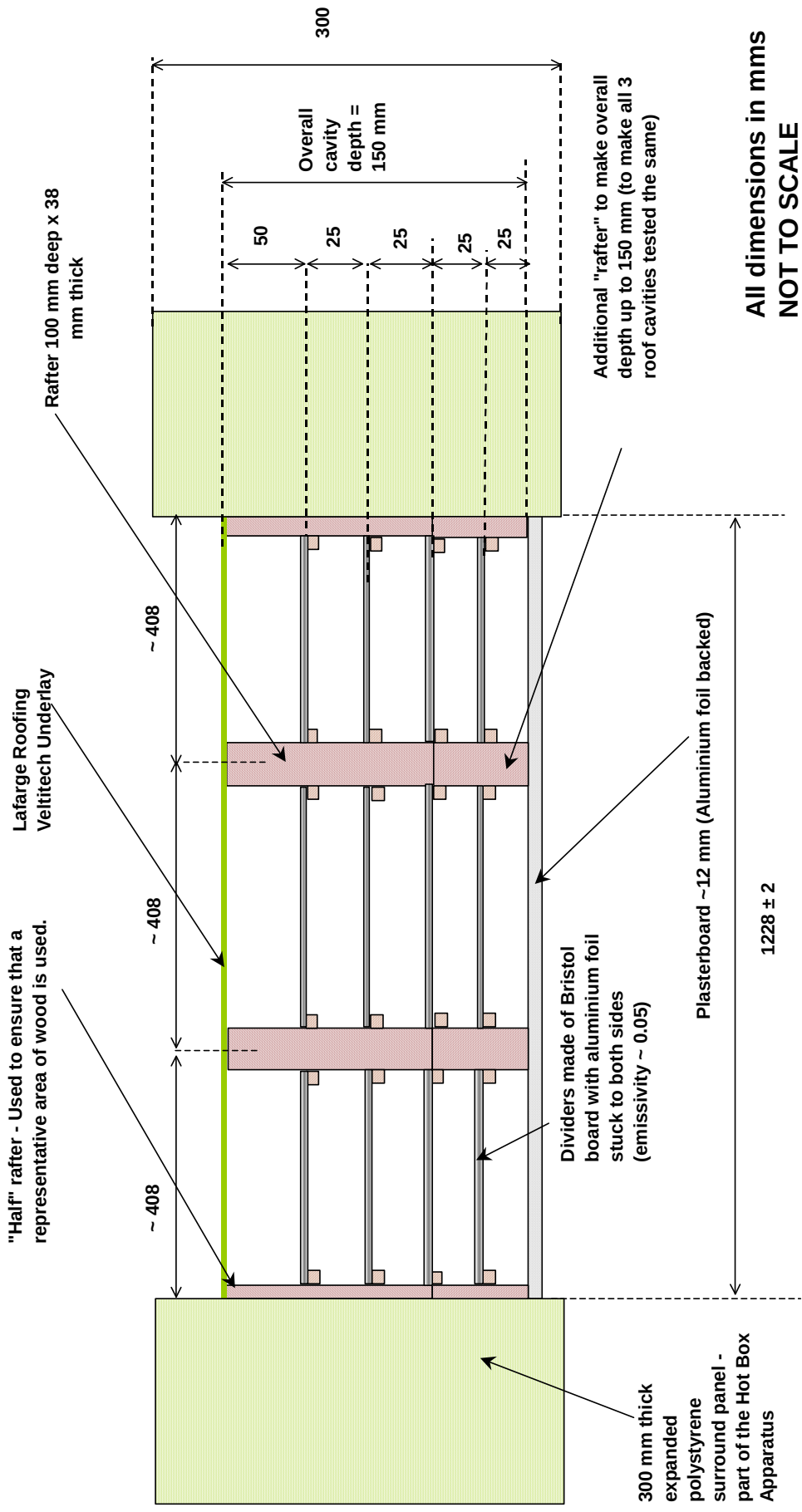


Figure 10 Cross section sketch of test element insulated with Knauf Rafter Roll 32 glass fibre



All dimensions in mm
NOT TO SCALE

Figure 11 Cross section sketch of test element insulated with reflective air cavities only



All dimensions in mm
NOT TO SCALE

Table 4 A typical set of experimental measured values

R058A		Holder panel number 4			Data entered by.....				GB		Service number...			PP31/DTI Project/1										
Triso-Super 10 - Vertical - Closed																			Data entry checked by..... R. Williams					
1	Date & Time	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Holder thermal conductivity data from 610 results								
	Specimen area	Holder Th	Surround	Surface	Power	Hot	Cold	Surface	Hot	Cold	diff	Hot	Cold	diff	Hot	Cold	Thermal Cond	Thermal Trans	Surface Resistance					
	(m²)	(W/m.K)	(mb)	(mb)	(W)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(W/m².K)	(W/m².K)	(m².K/W)					
13/02/2007 23:08	1.830	0.0335	0.0	0.0	26.193	21.786	2.873	20.581	3.091	22.062	2.725	21.704	2.805	5.70	0.56									
14/02/2007 01:08	1.830	0.0335	0.0	0.0	26.133	21.779	2.786	20.572	3.007	22.057	2.607	21.698	2.711	-0.40	0.56									
14/02/2007 03:08	1.830	0.0335	0.0	0.0	26.141	21.772	2.845	20.570	3.067	22.056	2.712	21.690	2.784	-0.10	0.56									
14/02/2007 05:08	1.830	0.0335	0.0	0.0	26.084	21.766	2.822	20.568	3.044	22.049	2.668	21.689	2.752	0.00	0.56									
14/02/2007 07:08	1.830	0.0335	0.0	0.0	25.976	21.772	2.813	20.569	3.036	22.053	2.661	21.693	2.746	3.10	0.56									
Averages	1.830	0.0335	0.0	0.0	26.105	21.775	2.828	20.572	3.049	22.055	2.675	21.695	2.760	1.66	0.56									

Date & Time	Total power Corfor	Surround Hot	Surround Cold	Surface Hot	Surface Cold	Power through Insert minus BL%	Holder Hot surface temp	Holder Cold surface temp	Surface Temp diff	Air Hot	Air Cold	diff	Hot	Cold	diff	Hot	Cold	Thermal Cond	Thermal Trans	Surface Resistance
Area of specimen	1.8296	m²				Thick @ edge		162.00	mm											
Area holder	3.9580	m²				Holder thickness		0.298	m											
Elfth	n/a	mm				Baffle Emis. Hot		0.94												
13/02/2007 23:08	26.172	21.786	2.873	2.786	17.186	20.581	3.091	17.490		22.062	2.725	19.337	21.829	2.733	19.095	21.704	2.805	0.537	0.492	0.133
14/02/2007 01:08	26.134	21.779	2.786	2.786	17.113	20.572	3.007	17.566		22.057	2.607	19.450	21.821	2.619	19.203	21.698	2.711	0.532	0.487	0.134
14/02/2007 03:08	26.142	21.772	2.845	2.845	17.149	20.570	3.067	17.503		22.056	2.712	19.344	21.817	2.719	19.098	21.690	2.784	0.536	0.491	0.133
14/02/2007 05:08	26.084	21.766	2.822	2.822	17.084	20.568	3.044	17.524		22.049	2.668	19.381	21.813	2.677	19.137	21.689	2.752	0.533	0.488	0.133
14/02/2007 07:08	25.965	21.772	2.813	2.813	16.958	20.569	3.036	17.533		22.053	2.661	19.392	21.815	2.670	19.145	21.693	2.746	0.529	0.484	0.134
	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Av.Values	26.099	21.775	2.828	2.828	17.098	20.572	3.05	17.52		22.06	2.67	19.38	21.82	2.68	19.14	21.69	2.76	0.533	0.488	0.133
Variation	0.80%	0.020	0.087	0.087	1.34%	0.013	0.084	0.43%		0.013	0.118	0.58%	0.015	0.114	0.56%	0.015	0.095	1.58%	1.60%	0.002
Surround temp difference		18.947	°C		9.345	W/m²														
Surround mean temperature		12.301	°C																	
Standardised U-value (to 0.17 m².K/W)																0.489				

Holder thermal conductivity data from 610 results

Table 5 Measured and calculated U-values of the four insulated roof systems.

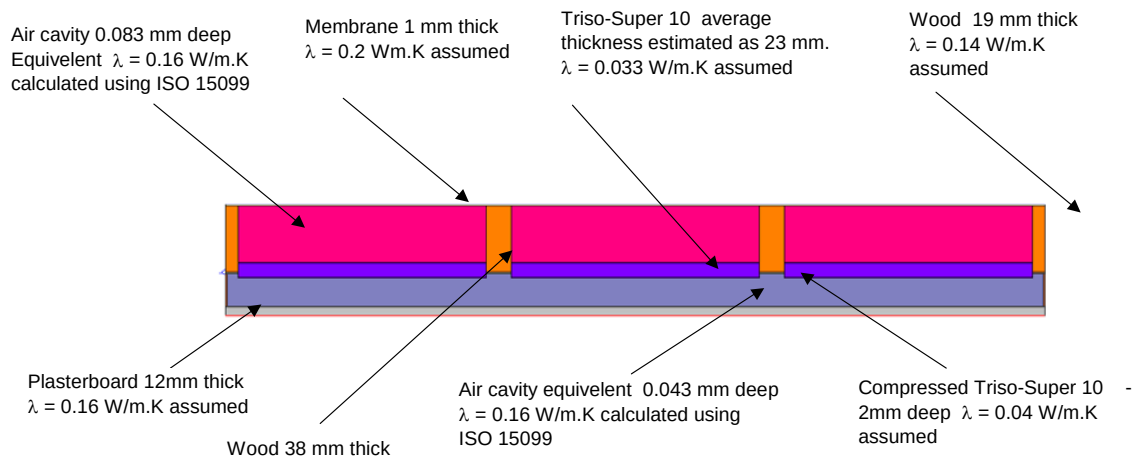
Hot Box test number	NPL Specimen number	Description of test element	Heat flow direction	Environmental [1] temperature difference (°C)	Measured standardised thermal transmittance (W/m ² .K)	Calculated thermal transmittance - (using THERM & ISO 15099) (W/m ² .K)	Assumptions made in calculating the U-value
1	R058A	Triso-Super 10 - Vertical - Air vent closed	Horizontal	19.14	0.489	0.53	* Triso-Super 10 assumed to be a uniform slab of insulation 23 mm thick with a λ of 0.033 W/m.K * It's outer surfaces were assumed to have emittances of 0.05
2	R058B	Triso-Super 10 - 45 degrees - Air vent closed	Up	19.14	0.514		
3	R058D	Triso-Super 10 - Horizontal - Air vent closed	Up	19.31	0.529		
4	R058E	Triso-Super 10 - 45 degrees - Air vent open	Up	19.10	0.559		
5	R058F	Triso-Super 10 - Horizontal - Air vent closed	Down	19.00	0.347		
6	R059A	Celotex - Vertical - Air vent closed	Horizontal	19.33	0.256	0.27	* The emittance of the foil covering of the insulation was assumed to be 0.2. * λ of the insulation was assumed to be 0.023 W/m.K. * Thickness of the insulation was taken as 100 mm
7	R059B	Celotex - 45 degrees - Air vent closed	Up	19.33	0.260		
8	R059C	Celotex - Horizontal - Air vent closed	Up	19.59	0.261		
9	R059D	Celotex - 45 degrees - Air vent open	Up	19.25	0.269		
10	R059E	Celotex - Horizontal - Air vent closed	Down	19.12	0.232		
11	R060A	Air cavity - Vertical - Air vent closed	Horizontal	19.31	0.334	0.36	* The emittance of the aluminium foil was assumed to be 0.05
12	R060B	Air cavity - 45 degrees - Air vent closed	Up	19.30	0.357		
13	R060C	Air cavity - Horizontal - Air vent closed	Up	19.63	0.417		
14	R060D	Air cavity - 45 degrees - Air vent open	Up	19.36	0.392		
15	R060E	Air cavity - Horizontal - Air vent closed	Down	19.17	0.268		
16	R061A	Glass fibre - 45 degrees - Air vent closed	Up	19.42	0.333	0.35	* λ of the glass fibre was assumed to be 0.034 W/m.K
17	R061B	Glass fibre - 45 degrees - Air vent open	Up	19.38	0.341		

Note [1] For the definition of environmental temperatures see BS EN ISO 8990 Annex A

5.4 U-values modelled using 2D Finite Element Analysis (FEA)

As a cross check, the U-values (in the 45 degree orientation) of the roof sections that had been measured in the hot box were calculated. The thermal resistance of the air cavities were calculated using the procedures in ISO 15099 and the overall U-value of the roof structure was simulated using the 2D Finite Element Analysis software tool THERM5, produced by the Windows and Daylighting Group of the Lawrence Berkeley Laboratory in the USA. A number of assumptions had to be made and the most important of which are identified in Table 5. A manual, iterative method was used to ensure the air cavity thermal resistance value associated with the appropriate air cavity temperature difference was used in the 2D FEA model. An example of a THERM5 model can be seen in Figure 12. The results of the 2D Finite Element Modelling can be seen in Table 5.

Figure 12 THERM Model of Roof section insulated with Triso-Super 10



6 Temperature cycling measurements carried out in a heat flow apparatus.

6.1 Description of apparatus and control system

These measurements were carried out in a LaserComp FOX 600, 610 mm square, single specimen, Heat Flow Meter apparatus, using control and acquisition software specifically written by the manufacturer for this project. This apparatus incorporates 5 heat flux transducers on both surface plates and five associated temperature sensors to measure the plate temperatures. It conforms to the requirements of ISO 8301, EN 12667. A simple, schematic diagram of the apparatus can be seen in Figure 13.

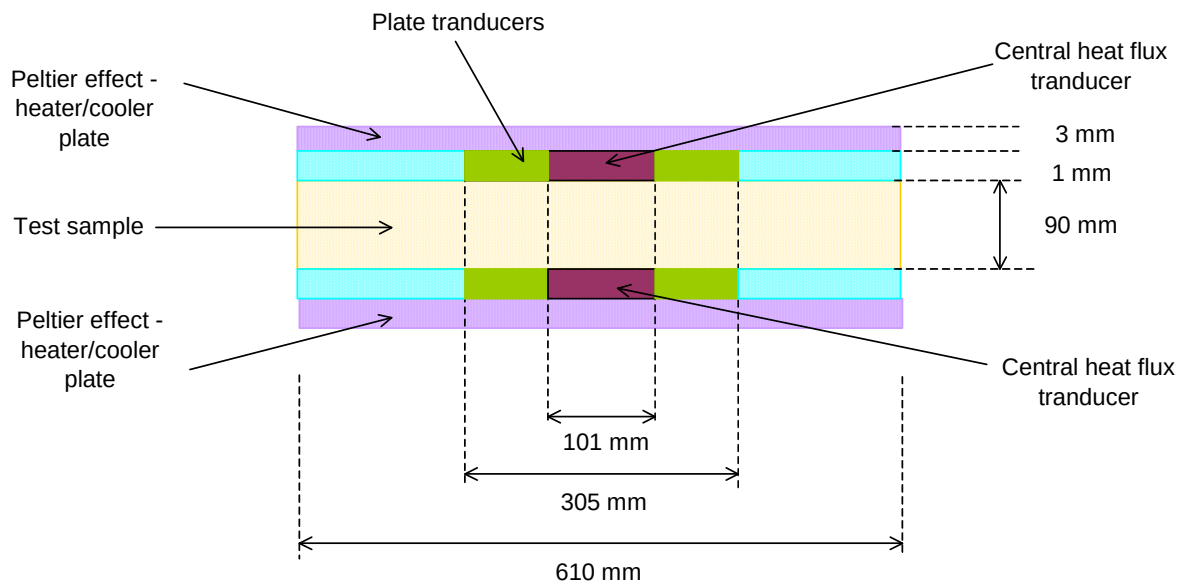
The special software allowed the following conditions to be imposed on the specimen:-

- i. The temperature of one plate held constant and the other cycled, over a period of 24 hours, at temperatures always higher than that of the plate held constant.
- ii. The temperature of one plate held constant and the other cycled, over a period of 24 hours, at temperatures that were both higher and lower than the one being held constant.

- iii. The temperature of one plate held constant and the other cycled, over a period of 24 hours, at temperatures always lower than that of the plate that was held constant

During the measurements the instantaneous heat flux (W/m^2) and temperature of the two central heat flux transducers were recorded approximately every 6 seconds.

Figure 13 Sketch of the LaserComp FOX 600 heat flow meter hot plate apparatus



6.2 Overview of specimens and measurements

The thermal performance of a low density glass fibre insulation specimen (10 kg/m^3) and an 85 mm deep air cavity insulated with Actis Triso-Super 10 installed centrally, were compared when the temperature of one of the bounding surfaces of the test sample was cycled as described in section 6.1. These measurements were carried out in the apparatus described in section 6.1. The plate temperatures and cycling regimes used for these measurements are also given in Table 6.

6.3 Heat flow meter steady state results.

The results for these measurements can be seen in Table 6. The marked difference between the thermal resistance measured with heat flow up and down for the air cavity insulated with the Triso-Super 10 material is the most interesting feature of these results.

6.4 Heat flow meter temperature cycling measurements

The results of these measurements can be seen in Figure 14, Figure 15, Figure 16, Figure 17, Figure 18 and Figure 19 and they are summarised in Table 6.

Table 6 Results of the heat flow meter apparatus measurements

Test number	Specimen description	Test description	Lower plate minimum temperature (°C)	Lower plate maximum temperature (°C)	Upper plate minimum temperature (°C)	Upper plate maximum temperature (°C)	Mean temperature (°C)	Temperature difference (°C)	Cycling temperature range (°C)	Average temperature difference across specimen during cycling (°C)	Heat flow direction °C	Thermal resistance (m ² .K)/W	W.hrs in 24 hours
1	Glass fibre (0.1m thick & 10kg/m ³)	Steady state	20	20	0	0	10	20	-	-	Up	2.192	-
2	Glass fibre (0.1m thick & 10kg/m ³)	Steady state	0	0	20	20	10	20	-	-	Down	2.178	-
3	Glass fibre (0.1m thick & 10kg/m ³)	Steady state	35	35	15	15	25	20	-	-	Up	1.985	-
4	Glass fibre (0.1m thick & 10kg/m ³)	Steady state	15	15	35	35	25	20	-	-	Down	1.977	-
5	Glass fibre (0.1m thick & 10kg/m ³)	Cycling	25	25	0	20	-	-	20	15	Up	-	1.75
6	Glass fibre (0.1m thick & 10kg/m ³)	Cycling	25	25	15	35	-	-	20	5	Up & Down	-	1.36
7	Glass fibre (0.1m thick & 10kg/m ³)	Cycling	25	25	30	50	-	-	20	15	Down	-	-2.03
8	ACTIS Triso-Super 10 in 0.085m cavity	Steady state	20	20	0	0	10	20	-	-	Up	1.734	-
9	ACTIS Triso-Super 10 in 0.085m cavity	Steady state	0	0	20	20	10	20	-	-	Down	2.471	-
10	ACTIS Triso Super 10 in 0.085m cavity	Steady state	35	35	15	15	25	20	-	-	Up	1.704	-
11	ACTIS Triso-Super 10 in 0.085m cavity	Steady state	15	15	35	35	25	20	-	-	Down	2.194	-
12	ACTIS Triso-Super 10 in 0.085m cavity	Cycling	25	25	0	20	-	-	20	15	Up	-	1.98
13	ACTIS Triso-Super 10 in 0.085m cavity	Cycling	25	25	15	35	-	-	20	5	Up & Down	-	1.20
14	ACTIS Triso-Super 10 in 0.085m cavity	Cycling	25	25	30	50	-	-	20	15	Down	-	-1.68

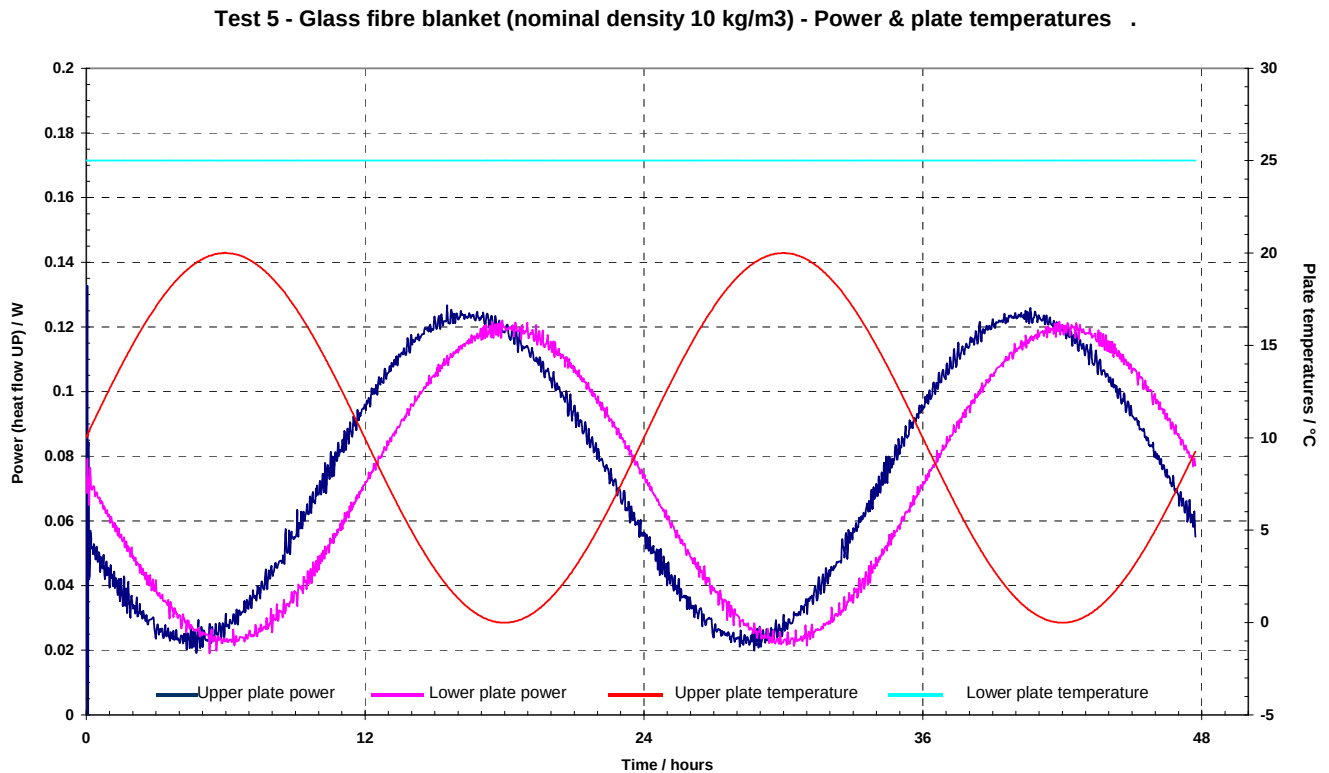
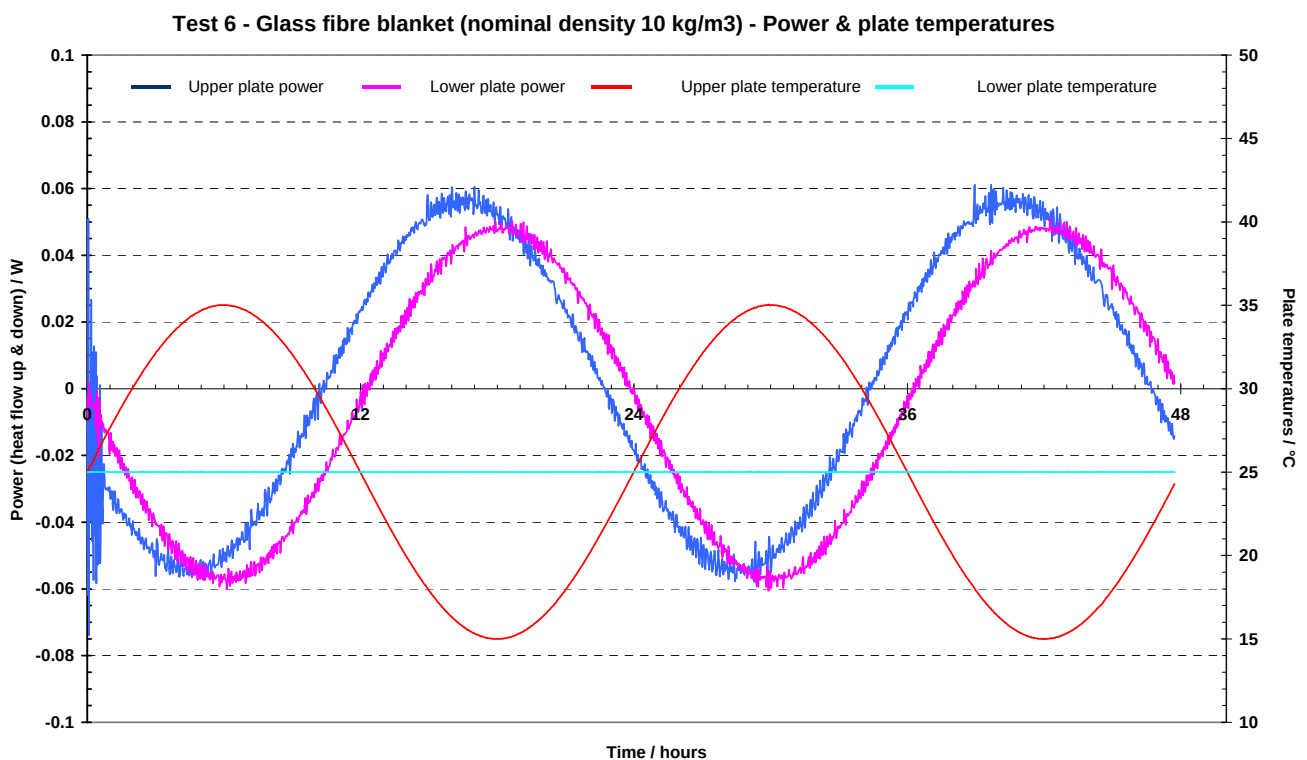
Figure 14 Test 5 Cycling glass fibre – Mean temperature 10 °C ± 10 °C**Figure 15 Test 6 Cycling glass fibre -Mean temperature 25 °C ± 10 °C**

Figure 16 Test 7 Cycling glass fibre - Mean temperature $40\text{ }^{\circ}\text{C} \pm 10\text{ }^{\circ}\text{C}$

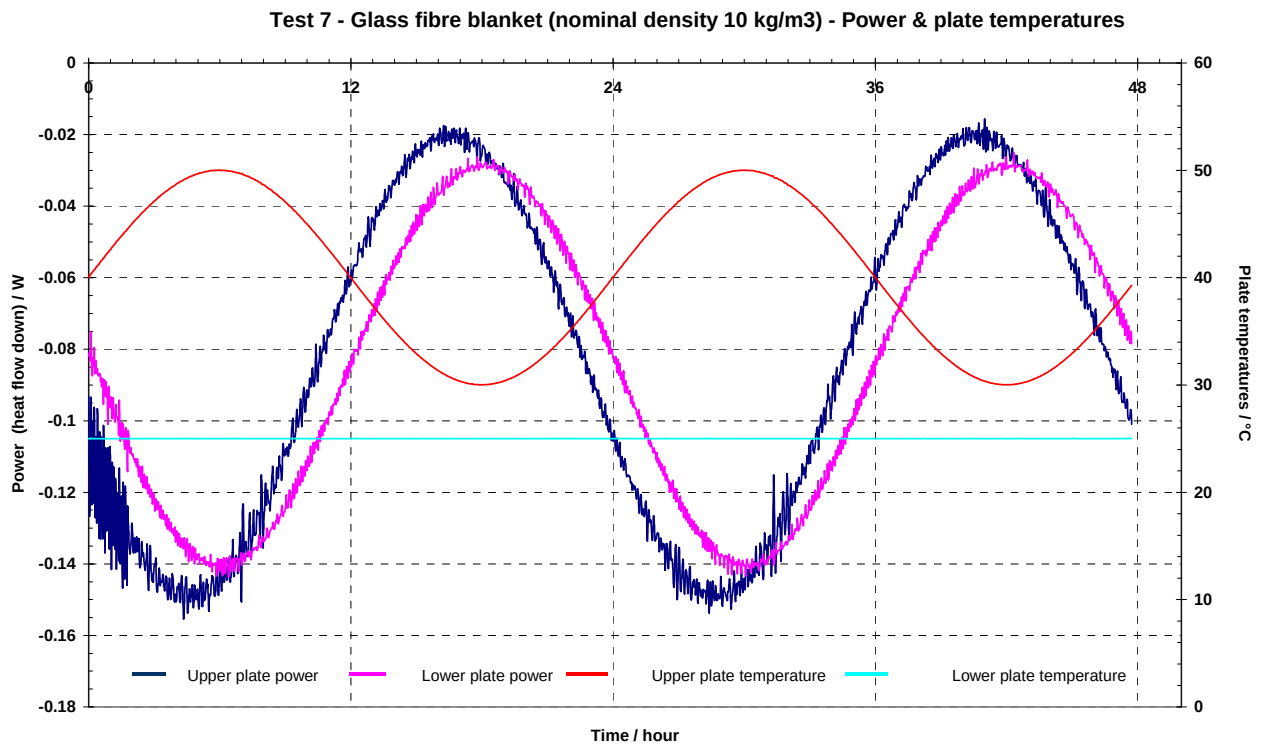


Figure 17 Test 12 Cycling Actis Triso-Super 10 - Mean temperature $10\text{ }^{\circ}\text{C} \pm 10\text{ }^{\circ}\text{C}$

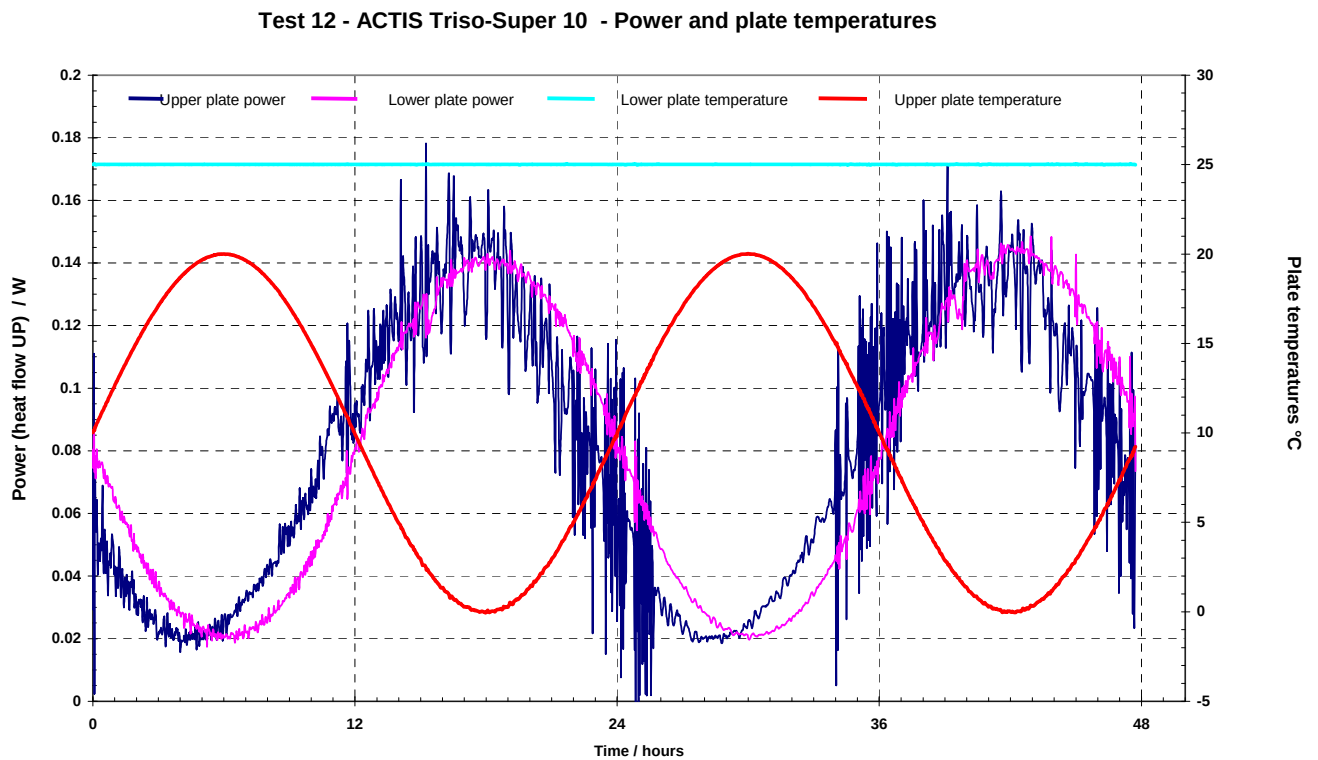
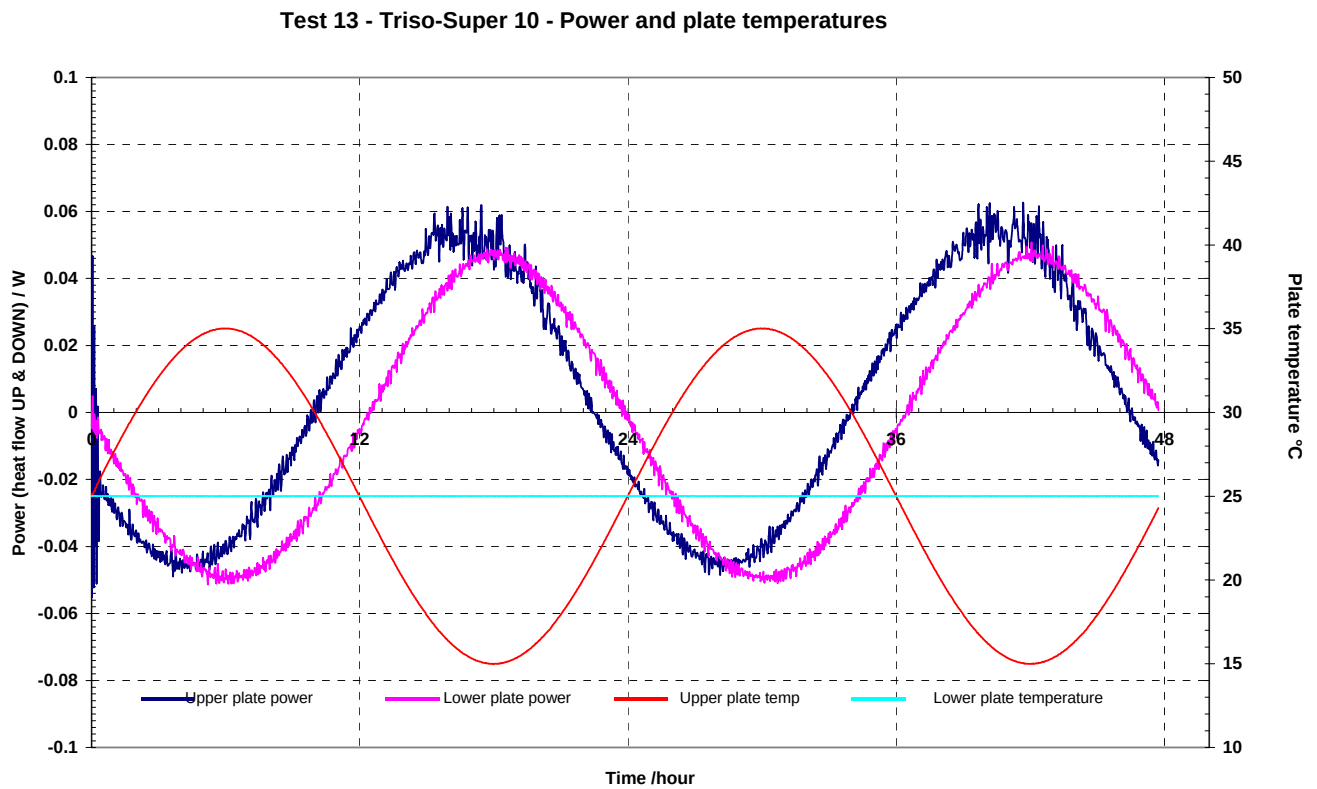
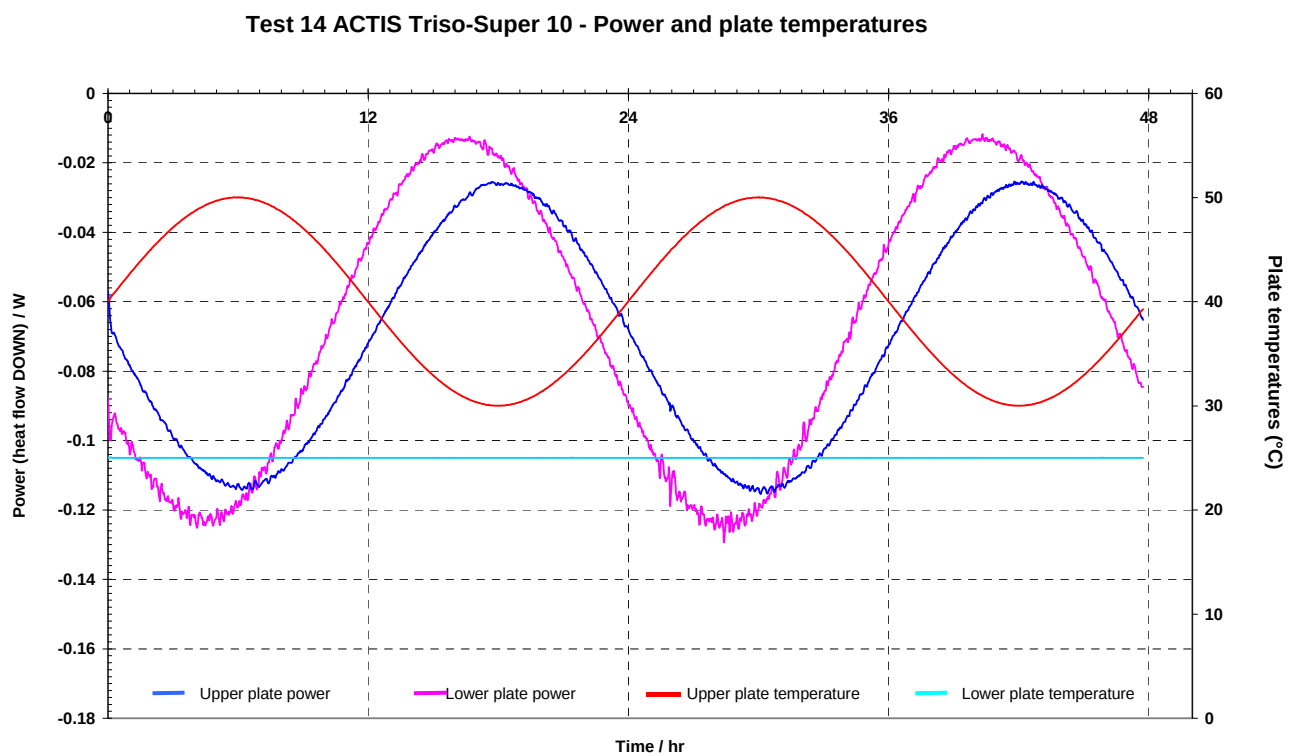


Figure 18 Test 13 Cycling Actis Triso-Super 10 Mean temperature $25\text{ }^{\circ}\text{C} \pm 10\text{ }^{\circ}\text{C}$ **Figure 19 Test 14 - Cycling Actis Triso-Super 10 Mean temperature $40\text{ }^{\circ}\text{C} \pm 10\text{ }^{\circ}\text{C}$** 

7 Discussion of results

7.1 Hot Box results

7.1.1 The measured U-values

The U-value results of the all the different roof systems are consistent with predictions of their thermal performance based on combining the various steady-state thermal resistances of the materials and air cavities, using well-established methodologies. The agreement between the measured U-values and those calculated using the convective correlations given in ISO 15099 to calculate the thermal resistance of unventilated air cavities, the thermal resistance of the various components and the two dimensional finite element analysis software tool THERM to combine them, support this conclusion. Those measured and calculated values are shown in Table 5.

7.1.2 The effect of direction of heat flow

The size of the effect of the direction of heat flow on the measured U-value once again reflects the relative importance of the thermal resistance of the air cavities to the overall thermal resistance. The values given in Table 7 show the Actis Triso-Super 10 insulated roof behaving in a similar way to the roof insulated only with air cavities, whereas the roofs with the Celotex and Glass fibre show a smaller effect on U-value of the direction of heat flow. In circumstances where the roof is hotter than the inside of the building the systems employing large air cavities will have much improved thermal properties. The U-value of the Actis Triso-Super 10 insulated roof was about 36% lower (see Table 7) with downward heat flow which is the same as the improvement in thermal resistance of the air cavity insulated with Triso-Super 10 measured in the heat flow meter apparatus (see Table 8).

7.1.3 Effect of allowing air flow into the external air cavity

The effect on the measured U-values of the small airflow induced into the outer cavity through 25 mm wide pierced metal strips fixed to the top and bottom of the roof structure, (see Figure 7) can also be seen in Table 7. It increased the U-value of the Tri-Iso Super 10 and the air cavity roof by about 9% and the Celotex and Glass Fibre insulated roofs by about 3% which again reflects the relative importance of that external air cavity to the overall thermal resistance of the system.

Table 7 Effect on measured U-value of orientation; air infiltration; direction of heat flow

Hot Box test number	NPL Specimen number	Description of test element	Heat flow direction	Environmental ^[1] temperature difference (°C)	Measured standardised thermal transmittance (W/m ² .K)	% difference to the U-value measured with horizontal heat flow.	% difference resulting from the small air flow in the external air cavity.	% change in U-value of horizontal cavity with downwards flowing heat transfer.
1	R058A	Triso-Super 10 - Vertical - Air vent closed	Horizontal	19.14	0.489			
2	R058B	Triso-Super 10 - 45 degrees - Air vent closed	Up	19.14	0.514	-5.1		
3	R058D	Triso-Super 10 - Horizontal - Air vent closed	Up	19.31	0.529	-8.2		
4	R058E	Triso-Super 10 - 45 degrees - Air vent open	Up	19.10	0.559		-8.8	
5	R058F	Triso-Super 10 - Horizontal - Air vent closed	Down	19.00	0.347	29.0		34.4
6	R059A	Celotex - Vertical - Air vent closed	Horizontal	19.33	0.256			
7	R059B	Celotex - 45 degrees - Air vent closed	Up	19.33	0.260	-1.6		
8	R059C	Celotex - Horizontal - Air vent closed	Up	19.59	0.261	-2.0		
9	R059D	Celotex - 45 degrees - Air vent open	Up	19.25	0.269		-3.5	
10	R059E	Celotex - Horizontal - Air vent closed	Down	19.12	0.232	9.4		11.1
11	R060A	Air cavity - Vertical - Air vent closed	Horizontal	19.31	0.334			
12	R060B	Air cavity - 45 degrees - Air vent closed	Up	19.30	0.357	-6.9		
13	R060C	Air cavity - Horizontal - Air vent closed	Up	19.63	0.417	-24.9		
14	R060D	Air cavity - 45 degrees - Air vent open	Up	19.36	0.392		-9.8	
15	R060E	Air cavity - Horizontal - Air vent closed	Down	19.17	0.268	19.8		35.7
16	R061A	Glass fibre - 45 degrees - Air vent closed	Up	19.42	0.333			
17	R061B	Glass fibre - 45 degrees - Air vent open	Up	19.38	0.341		-2.4	

7.2 Heat Flow Meter measurements and the non-steady state results.

The measured values are shown in Table 6 and a summary of the analysis carried out of these data are shown in Table 8. The energy used over a 24 hour period to cycle the glass fibre and Triso-Super 10 insulated air cavity was derived from the area under the curves shown in Figure 14, Figure 15, Figure 16, Figure 17, Figure 18 and Figure 19, using a graphical technique.

The thermal resistance values of the 100 mm thick low-density glass fibre and the 85 mm thick, Triso-Super 10 insulated air cavity, are in good agreement with values measured previously both in the heat flow meter apparatus and the hot box. When the thermal resistance values measured at the same temperature, with upward heat flow and downward heat flow are normalised to the same temperature –(see Table 8), the thermal resistance of the glass fibre is shown to be independent of heat flow direction and the Actis Triso-Super 10 insulated air cavity to be strongly dependent on heat flow direction as expected.

The energy used to cycle these systems over a 24 hour period will be dependent on:

- i. Temperature difference
- ii. Mass
- iii. Thermal resistance (which is dependent on mean temperature for both systems and the temperature difference for the Triso-Super 10 insulated air cavity).
- iv. Specific heat.

To compare how these two subsystems are behaving dynamically, the thermal resistance at the “mean” temperature of the cycled samples has had to be derived from the measured steady state values for both materials for both the only heat flow up and only heat flow down situations. See Table 8. The figures in this table show that for heat flow up, at a mean temperature of 17.5 °C, the thermal resistance of the glass fibre specimen is 18% higher than the Tri-Iso Super 10 insulated air cavity, however, the Watt hours used over 24 hours was only 13% less for the glass fibre sample than for the Triso-Super 10. This small discrepancy could be related to the fact that the thermal resistance of an insulated air cavity will increase (non-linearly) as the temperature difference across it gets smaller and that the minimum temperature difference in this case is 5°C.

The figures in this table also show that for the heat flow down situation, at a mean temperature of 32.5°C, that while the thermal resistance of the glass fibre specimen is 10% lower than for the Triso-Super 10 insulated air cavity, the Watt hours used over 24 hours was 17% more for the glass fibre sample. This discrepancy could again be related to the fact that the thermal resistance of an insulated air cavity increases (non-linearly) as the temperature difference across it gets smaller. The minimum temperature difference in this case is again 5°C.

The graphs for the situation where the upper plate was cycled above and below the temperature of the fixed temperature plate highlight the asymmetrical nature of the air cavity thermal resistance. With the glass fibre sample (Figure 14) the Watts against time curve is symmetrical around 0 watts. For the Triso-Super 10 insulated air cavity (Figure 15) it can be seen that more power is being transferred on the heat-flow-up cycle than for the heat-flow-down-cycle.

There are a number of interesting features of the graphs plotted for the temperature cycling data that have not yet been analysed. These are:

- Phase difference between the power entering and leaving the upper and lower heater/cooler plates.
- Amplitude difference between the power entering and leaving the upper and lower heater/cooler plates.
- The periods of erratic power flows exhibited by some of the graphs could be associated with the onset of convection.

Table 8 Analysis of the heat flow meter apparatus measurements

Glass fibre (100 mm thick ~ 10 kg/m³)		
Thermal resistance at mean temperature 10 °C heat flow UP (measured - steady state)	2.192	m ² .K/W
Thermal resistance at mean temperature 25°C heat flow UP (measured - steady state)	1.985	m ² .K/W
Thermal resistance at mean temperature 17 °C heat flow UP (Interpolated - steady state)	2.095	m ² .K/W
Thermal resistance at mean temperature 10 °C heat flow DOWN (measured - steady state)	2.178	m ² .K/W
Thermal resistance at mean temperature 25°C heat flow DOWN (measured - steady state)	1.977	m ² .K/W
Thermal resistance at mean temperature 32°C heat flow DOWN (extrapolated - steady state)	1.883	m ² .K/W
Thermal resistance at mean temperature 17°C heat flow DOWN (interpolated - steady state)	2.084	m ² .K/W
% difference between (R @ 17 °C HF UP & R @ 17°C HF DOWN)/ (R @ 17 °C HF UP)	0.5	%
(W.hr in 24 hours) - mean temp ~ 17 °C heat flow UP (Measured - temperature cycling)	1.75	W.hr
(W.hr in 24 hours) - mean temp ~ 32 °C heat flow DOWN (Measured - temperature cycling)	2.03	W.hr
Tri-Iso Super 10 in centre of a 85 mm deep air cavity		
Thermal resistance at mean temperature 10 °C heat flow UP (measured - steady state)	1.734	m ² .K/W
Thermal resistance at mean temperature 25°C heat flow UP (measured - steady state)	1.704	m ² .K/W
Thermal resistance at mean temperature 17 °C heat flow UP (Interpolated - steady state)	1.720	m ² .K/W
Thermal resistance at mean temperature 10 °C heat flow DOWN (measured - steady state)	2.471	m ² .K/W
Thermal resistance at mean temperature 25°C heat flow DOWN (measured - steady state)	2.194	m ² .K/W
Thermal resistance at mean temperature 32°C heat flow DOWN (extrapolated - steady state)	2.065	m ² .K/W
Thermal resistance at mean temperature 17°C heat flow DOWN (interpolated - steady state)	2.342	m ² .K/W
% difference between (R @ 17 °C HF UP - R @ 17 °C HF DOWN)/R @ 17 °C HF UP	-36.1	%
(W.hr) - mean temp ~ 17 °C heat flow UP	1.98	W.hr
(W.hr) - mean temp ~ 32 °C heat flow Down	1.68	W.hr
Relationship between Thermal resistance and Energy used to cycle test elements over a 24 hour period		
Mean temperature 17 °C HF UP - ((R glass fibre - R Tri-Iso)/ Rglass fibre)	18	%
Mean temperature 17 °C HF UP - ((W.hr glass fibre - W.hr Tri-Iso)/ W.hr glass fibre)	-13	%
Mean temperature 32°C HF DOWN - ((R glass fibre - R Tri-Iso)/ Rglass fibre)	-10	%
Mean temperature 32°C HF DOWN - ((W.hr glass fibre - W.hr Tri-Iso)/ W.hr glass fibre)	17	%

8 Summary of project and conclusions

8.1 Summary of project

- a) The U-values of a representative roof section insulated with four different insulation systems have been measured in the NPL rotatable hot-box facility. The insulation systems tested were:
 - Actis Triso-Super 10
 - Celotex TUFF-R™ GA 3050 rigid polyisocyanurate foam
 - Glass fibre Knauf Rafer Roll 32
 - Reflective air cavities formed by 2 mm cardboard covered on both sides with aluminium foil.
- b) The U-value measurements were carried out in the following orientations:
 - Test element vertical - Horizontal heat flow - Air vent closed
 - Test element @ 45 degrees - Heat flow up - Air vent closed
 - Test element @ 45 degrees - Heat flow up - Air vent **open**
 - Test element horizontal - Heat flow up - Air vent closed
 - Test element horizontal - heat flow down - Air vent closed
- c) The U-value of each of the roof structures in the 45 degree orientation, were also calculated using the thermal conductivity data of the materials, the procedures in BS ISO 15099 to derive air cavity thermal resistances and the Lawrence Berkeley Laboratory 2D FEA software - THERM5.
- d) Steady state thermal resistance measurements and temperature cycling, energy consumption measurements were carried out in a LaserComp FOX 600, a 610 mm square, single specimen, Heat Flow Meter (HFM) apparatus, using special control and acquisition software written by the manufacturer for this project. The measurements were carried out on two specimens:
 - 100 mm thick glass fibre (10 kg/m³)
 - 85 mm deep air cavity with a layer of Actis Triso-Super 10 material fixed in the centre of the cavity.

The HFM apparatus measurements carried out were:

Steady state thermal resistance measurements:

- i) Mean temperature 10 °C with heat flow up.
- ii) Mean temperature 10 °C with heat flow down
- iii) Mean temperature 25 °C with heat flow up.
- iv) Mean temperature 25 °C with heat flow down

Thermal cycling measurements.

- v) Lower surface constant 25 °C upper surface 10 °C ± 10 °C
- vi) Lower surface constant 25 °C upper surface 25 °C ± 10 °C
- vii) Lower surface constant 25 °C upper surface 40 °C ± 10 °C

- e) Brief explanations of the following were given:
 - i) The role of the three modes of heat transfer in the roof structures.
 - ii) Factors that effect the thermal resistance of air cavities.
- f) The various methods that could be used to quantify the thermal performance of insulation systems based on the use of reflective surfaces are discussed (Section 3).

8.2 Conclusions

- 1) The mechanisms by which reflective surfaces increase the thermal resistance of air cavities are well understood.
 - The use of low emittance surfaces to increase the thermal resistance of air cavities has a long history (Sir James Dewar's vacuum flask in 1882).
 - There are many "standard" methods of calculating the thermal resistance of air cavities that have one or more reflective surfaces from measured emittance values, temperature difference across the cavity, mean temperature and cavity orientation. These include BS EN 673, BS ISO 15099, BS EN ISO 6946 and the ASHRAE Book of Fundamentals).
- 2) The hot-box apparatus is capable of measuring the overall heat transfer through non-homogeneous structures that involve all three modes of heat transfer.

Traditionally the thermal conductivity (W/m.K) of a homogeneous material (e.g. expanded polystyrene) is measured in a hot-plate apparatus^[Note 1]. From the thermal conductivity value, various other thermal properties (e.g. thermal conductance, thermal resistance and U-value can be calculated using the thickness and standard surface heat transfer coefficients.

The purpose of a hot box apparatus^[Note 1] is to measure the overall heat transfer through non-homogeneous structures by measuring the temperature difference between the environments on either side of the structure, it's area and the heat flow through it.

The limitations of the hot-box method are as follows:

- It is not intended to quantify the effect of mass transfer (air infiltration). The thermal effect of air infiltration is traditionally determined by measuring the air infiltration rate through the structure and calculating the thermal effect of that airflow rate.
- It does not account for the effect of solar gain (e.g. through glazing)

The suitability of the hot-box apparatus to measure the thermal transmittance of structures insulated with all types of insulation has been demonstrated by the good agreement between the measured U-values of the roof structures and those calculated using typical material property data, air cavity thermal resistances calculated using BS ISO 15099 and a assumed low emittance and the 2D FEA software tool THERM.

Note[1] – Despite their similar sounding names, hot plate and hot-box apparatus are very different. A hot-plate apparatus (either guarded hot-plate or heat flow meter {HFM} hot-plate apparatus) measures the surface temperature difference across and the heat flow through, homogeneous samples measuring typically about 0.6 m x 0.6 m x 0.02 m to 0.2 m thick. A hot-box apparatus, however, measures the overall heat transfer, from the warm environment to the cold environment, through large, non-homogeneous structures. Specimens up to 2 m x 2 m x 0.3 m can be measured in the NPL facility – but apparatus exist that can measure even larger test elements

Those measured and calculated U-values have been extracted from Table 5 and summarised in Table 9 below which shows the calculated values between 0 and 5% higher than the measured.

It should be specially noted that one of these structures was insulated by a method that solely comprised air cavities and reflective surfaces.

Table 9 Comparison between measured and calculated U-values

NPL Specimen number	Description of insulation used in the roof structure. All measurements - Air vent closed - Specimen at 45 degrees.	Heat flow direction	Measured standardised thermal transmittance (W/m ² .K)	Calculated thermal transmittance - (using THERM & ISO 15099) (W/m ² .K) ^[1]	Assumptions made in calculating the U-value
R058B	Triso-Super 10	Up	0.51	0.53	* Triso Super 10 product assumed to be a uniform slab of insulation 23 mm thick * It's outer surfaces assumed to have an emittance of 0.05
R059B	Celotex	Up	0.26	0.27	* The emittance of the foil covering of the insulation assumed to have an emittance of 0.2; a the thermal conductivity of the insulation to be 0.023 W/m.K. and the thickness of the insulation was 100 mm
R060B	Air cavities only	Up	0.36	0.36	* The emittance of the aluminium foil was assumed to be 0.05
R061A	Glass fibre	Up	0.33	0.35	* The thermal conductivity of the glass fibre was assumed to be 0.034 W/m.K

- 3) No significant thermal advantage was observed for the insulated air cavity over the low-density glass fibre specimen during the temperature cycling measurements.

Dynamic thermal measurements of an air cavity insulated with Actis Triso-Super 10 and a 100 mm thick, low density glass fibre specimen, showed the power required to cycle their temperatures over a 24 hour period were within $\pm 17\%$ of each other, depending on direction of heat flow, with much of the difference being explained by differences in the thermal resistance at the average temperature of the sample during the cycling measurements. (See Table 8).

- 4) The hot box is the most effective method of determining the thermal resistance of air cavities insulated with non-geometrically regular, reflective insulation

Because of the difficulty of measuring the thermal resistance of non-geometrically regular products in a hot plate apparatus and difficulty in measuring the emittance of low emittance (often non-planar) surfaces it is concluded that the most effective method of determining the

thermal resistance of an air cavity, insulated with such products, is to measure the thermal resistance of the insulated air cavity using the hot-box apparatus.

- 5) The thermal resistance of structures with deep (> 20 mm) air cavities will be dependent on temperature difference and heat flow direction.

When the hot environment is above the cold environment there is a significant improvement air cavity thermal resistance. This is illustrated by the improvement in the measured U-values of the Triso-Super 10 insulated roof and the roof insulated only with air layers when the heat-flow was downward (see the results in Table 5). It should be noted, however, that the thermal resistance of air cavities would decrease when the temperature difference across them increases (see Table 1). This effect will be important when the thermal performance of a structure depends mainly on the thermal resistance of air cavities.

- 6) Possible reasons for the large differences between the thermal performance values measured with the standard measurement methods and the comparative measurement methods.
- i) Are comparative methods sensitive enough to discriminate between products?

It is important to determine if the method of comparing the power used to keep two roof-shaped structures, insulated with different products, exposed to the fluctuating outdoor climate, at the same internal temperature, is sensitive enough to discriminate between the thermal properties of the insulation materials being compared.

To determine if a method is able to discriminate between products, a sensitivity analysis of the thermal system should be carried out to determine:-

- What percentage of the energy used, goes through the floor, end walls and the cold bridging constructions (i.e. rafters)?
- What percentage of the measured energy (over a given period of time) goes into changing the temperature of the structure?
- What percentage of energy is lost through heating up the air infiltrating into the structure?
- Identifying these parameters will enable the percentage of the measured energy that goes through the product being characterised to be determined.

Some suggestions of how to identify the cause of these differences are given in Section 3.5.

- ii) Can a straightforward comparison of energy used to keep a special structure at a given temperature, while exposed to the outdoor climate, be used to compare products?

Extracting the thermal performance data for a specific component of a structure from the total energy required to keep that structure at a constant temperature when exposed to a real fluctuating climate is very complex. The EU PASSYS Project is an example of how this has been attempted in the past and is a good illustration of how complex that process is.^[Note 2]

[Note 2] "Experience from PASSYS and the use of MRQT" – D.van Dijk – EU Commission Joint Research Centre publication – System identification applied to building performance data.