STUDY REPORT

SR 233 (2010)

Investigation into the Performance of Urea Formaldehyde Foam Insulation

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1. EXECUTIVE SUMMARY

The findings from inspections of several houses to date confirm that although serious problems with UFFI installation process within New Zealand appear relatively rare, there are issues with the performance of the product within most, if not all, properties, where UFFI products have been used. This ranges from poor installation and areas that have been missed by the applicator, through to shrinkage of the foam, all of which significantly affect the thermal performance of the product and indeed the building. It is estimated that these effects can reduce the thermal effectiveness of the UFFI product by up to 60%.

Laboratory tests on both site samples and laboratory-prepared specimens have also indicated that the installed product does not meet the claimed performance specifications and may also be affected by high humidity conditions. There are also reports that the UFFI installation can affect the properties and performance of other building materials, such as paints, wall linings etc.

A review of the overseas literature has shown that the information regarding the health issues and effects of formaldehyde exposure from UFFI is unclear and inconsistent with many variables, such as airtightness, ventilation and construction type, affecting the results and opinions around the world.

2. SCOPE

Although Urea Formaldehyde Foam Insulation (UFFI) has been installed in New Zealand houses for over 25 years, there have been a number of unanswered questions regarding thermal performance, durability, installation and shrinkage, where independent research has either not been completed or is now decades old and may no longer be relevant to products currently available in New Zealand. There are also questions regarding the suitability of the foam for all common New Zealand house wall constructions and whether its installation might compromise aspects of the performance of the existing building.

The work outlined within this research project aims to address these questions over the performance and suitability of foam insulation in New Zealand timber-framed houses, which have never been fully investigated. The findings of this work would also enable EECA to provide information and guidance to consumers regarding the use of insulation products to improve the energy efficiency of existing buildings, and also consider whether or not to include the use of these products within EECA's residential retrofit programme.

3. INTRODUCTION

Urea formaldehyde foam insulation (UFFI) was originally developed in Europe in the 1950s for use as an insulation material in double brick/block cavities in house walls. Generally, it is made on-site from an aqueous mixture of urea-formaldehyde resin and a foaming agent / hardener, containing an acid catalyst, to produce a mixture with a consistency similar to shaving foam.[1-7] This foam is then injected into the wall, and cures to form an insulating foam plastic. A slight excess of formaldehyde is added to ensure complete curing with the urea to produce the urea-formaldehyde foam. The

excess formaldehyde is given off during the curing process, together with water, which is used within the foam slurry and is also a by-product of the curing process. The excess water and formaldehyde released during the process has been the basis of a number of complaints relating to UFFI both in New Zealand and overseas, together with claims of poor installation and inappropriate use in locations where it should not have been.[1-3, 7-13]

Internationally, these complaints included both health issues, where home-owners and tenants claimed that the exposure to formaldehyde was causing irritation to the eyes, nose and throat, and in extreme cases nausea, vomiting and nose bleeds, as well as material defects caused by the excess moisture, such as blistering and peeling paint, the appearance of fungal growth, discolouration of finishes and corrosion of electrical boxes. There were further claims that the foam breaks down within the cavity over time, releasing more formaldehyde and creating further health issues.[2,11]

Sufficient complaints were received in Canada and parts of the USA, particularly from people living in airtight homes where ventilation was low, that the authorities became concerned with the health implications and the use of UFFI was banned in the 1980s.[1,2,14,15]

UFFI was used in the 1970s, most extensively from 1975 to 1978, during the period of the Canadian Home Insulation Program (CHIP), when financial incentives were offered by the government to upgrade home insulation levels. It is estimated that over 100,000 homes in Canada were insulated with UFFI. Recent discussions between BRANZ and the Institute for Research in Construction – National Research Council of Canada have confirmed that UFFI is still banned in Canada under the Canadian Hazardous Products Act. The UFFI crisis in the 1970s/80s arose from the introduction of government subsidies for the insulation of uninsulated houses. The UFFI industry was unregulated, and UF resin manufacturers sold UF resin to blenders and formulators who derived their own products by including additional materials to reduce shrinkage. The modified resin was on-sold to installers. As a result of the way the ban was imposed in 1980, the IRC was not able to determine the critical factors in formaldehyde release, foam breakdown, and shrinkage. IRC expertise in the area has since been lost because the product was banned and there was no need for further work. [1-3, 14]

UFFI was also used in the US during the 70s, and has been used in Europe over the last thirty years, including the UK, where it was predominantly used in double brick/block construction. Although it is still used in Europe, where it appears it was never banned, the use of the product is not that widespread and other options are now available, for example mineral wool, beads and polyurethane foam. In the US, the Consumer Protection Safety Commission banned the sale of UFFI in 1982, followed by regulation that prohibited the sale of urea formaldehyde. However, in the following year, the US Court of Appeal overturned the decision due to there being no direct evidence between UFFI installations and health issues. The use of the product has since been very low and UFFI is not widely used in the US today. [2,14,16-23]

In the early 1980s, 72,000 Australian dwellings installed UFFI as an energy conservation measure in their walls or ceilings, but by the late 1980s this practice had significantly declined and UFFI is rarely used in Australia today. In Australia the national health guidelines are prepared by Australia's National Health and Medical Research Council (NHMRC), which recommended an indoor air quality guideline for formaldehyde in the 1980s. It was concerned with potential health effects associated with the use of the UFFI product, which included eye and respiratory tract irritation and reported carcinogenic effects in animals. Therefore a maximum indoor air quality level was recommended but does not appear to have been implemented at any stage.[10-12,24]

The health effects associated with UFFI and particularly the formaldehyde levels associated with the product have been debated throughout the world for some time and

there are many conflicting reports. It is generally agreed that the formaldehyde levels quickly reduce within the home shortly after installation when the home is well ventilated, but higher levels have been reported in more airtight homes several months after installation. There is also debate on whether the UFFI breaks down further with age, hence maintaining the higher levels of formaldehyde and causing further heath issues, associated with the formaldehyde. [1-3,11,17-35]

In New Zealand the DBH Determination 2008/35 on the UFFI product installed in a house in Tauranga stated that in accordance with section 188 of the Building Act 2004, [7-9]

- *some of the building work carried out under building consent No 73702 for which a Code Compliance Certificate was subsequently issued does not comply with Clauses B2, and E2, of the Building Code. Accordingly the territorial authority's decision to issue a Code Compliance Certificate is reversed:*
- *the un-consented building work (the installation of the foam insulation) does not comply with Clauses B2, E2, and F2 of the Building Code.*

There has been much debate between Territorial Authorities (TAs) following this Determination with most emphasis being on the UFFI filling the cavities in brick veneer constructions. Discussions with TA representatives indicate that Dunedin City, Christchurch City and Northland councils have subsequently put in place the requirement that the product requires a consent for use in brick veneer construction, based on the Determination. Other TAs are waiting for more information on the product prior to any further action.

Installers within New Zealand and overseas claim that despite high quality chemicals being used within the process, the consistency of the foamed product varied as it is prepared on site and was dependent on the skill of the installer, and therefore most of the problems associated with the UFFI product resulted from poor installation.[36] However, there is apparently little evidence to support these claims.

Airfoam, the sole UFFI installer within New Zealand, has since attempted to address this issue through the development and production of the AIRFOAMA method and apparatus, which they believe produces a perfectly mixed foam for reliability and a constant quality standard in foam production. Airfoam representatives have indicated that the franchisees have been using the new technology since 2008.

Discussions with Airfoam franchise operators indicate that the Airfoam UFFI can be installed for \$50-\$60 per m^2, giving a cost of approximately \$5,000 for a typical 3 bedroom house and \$2600 for a unit, compared to costs of \$70-\$100 per m^2 for other insulation installations involving relining of wallboards.

The experimental work outlined within this report comprised site inspections and laboratory investigations. Pre- and post-installation monitoring of the indoor air quality within retrofitted houses has not been carried out within this programme of work.

4. SITE VISITS

A series of site visits to observe and assess UFFI installations in New Zealand houses have been carried out by inspecting 23 houses in the Christchurch, Hamilton and Wellington / Lower North Island regions in late 2009 and early 2010. The houses inspected have been identified / provided through the BRANZ Helpline, EECA or from Airfoam directly and include UFFI installations dating back over the last 20+ years and with a variety of constructions and claddings.

The inspections have included a study of the impact of UFFI installation on aesthetic outcomes, such as wall linings or finishing timbers, and in cases where wallboards have been removed,

- durability assessment of structure including inspections of foam, pipes, cables and other building components;
- condition assessment of framing timber;
- investigation into the post-installation status of UFFI as it cures and the status of the in-situ whole-of-wall thermal resistance.

In each case, thermal imaging (FLIR P620) has been used to determine installation quality and whether all areas of external wall have been appropriately insulated. This technique gave a good indication of areas where the insulation was complete or missing, but required an appropriate temperature difference between external and internal environments to be most effective. As the weather was relatively mild during the inspections, it was not possible to make quantitative assessments of shrinkage. Performing surveys in winter would enable a more quantitative assessment to be carried out.

4.1 Inspection details

Although there have been a few reported cases where the Airfoam installation process has been problematic, such as in the case observed in Figure 1 and Figure 2, it appears that these cases are relatively rare occurrences. These issues are usually a result of installer error or lack of robust assessments prior to installation.

Figure 1: Example of serious installation problems (House W7)

Figure 2: Example of serious installation problems (House W7)

However, in every inspection undertaken by BRANZ there has been evidence of issues and problems relating to the performance of the installed UFF insulation. In some cases this was only minor, with missing foam in some difficult to access areas, such as soffits and in areas where there was atypical stud spacing. Home-owners mentioned that in some cases the installers had in fact pointed out that there were areas that they were unable to insulate.

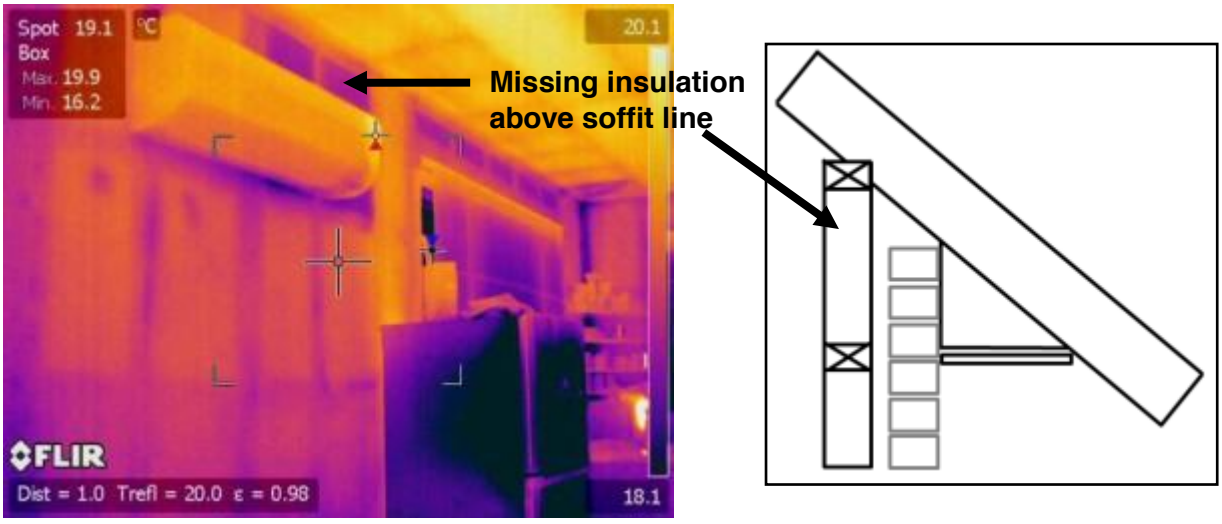

Figure 3: Thermal image identifying missing insulation in an upper wall above the soffit line (House W2)

Figure 4: Thermal image identifying missing insulation in another upper wall above the soffit line (House C7)

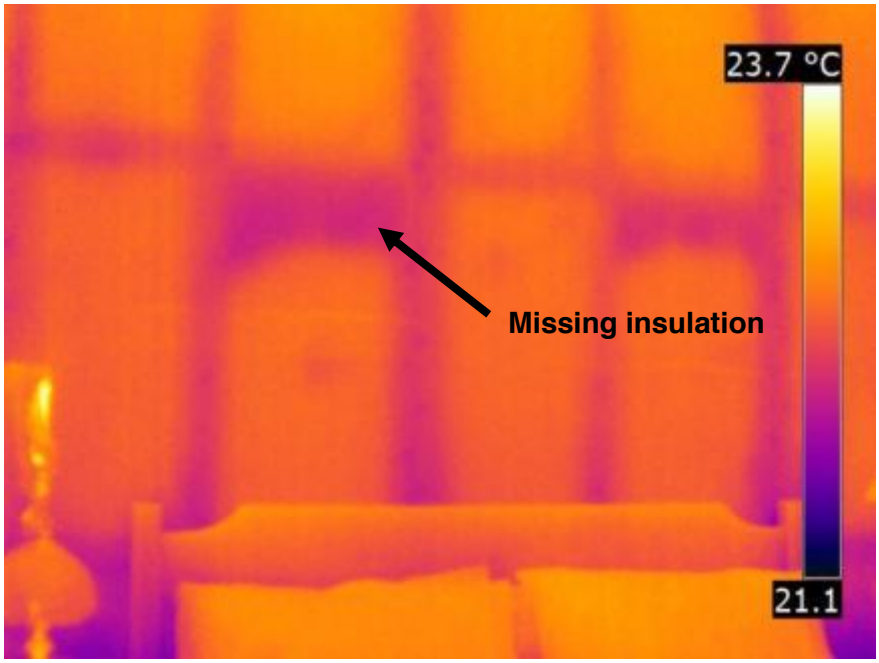

Figure 5: Thermal image identifying poor installation of Airfoam (House C5)

It was originally assumed that the walls were fully dry and that most of the shrinkage had already occurred. However, at least two of the houses surveyed that were insulated 20 years ago showed that the shrinkage appears to be greater than that occurring in the houses insulated more recently. Although the current foam formulation may be shrinking less than previous formulations, the literature and laboratory work to date suggest that the foam could continue to break down and shrink with time under certain conditions.

4.1.1 Case Studies

(House C4) *A weatherboard house with building paper, insulated in April 2006*. There were a number of areas where insulation was missing and it appeared that the density of insulation was variable throughout the house. There appeared to be some cracks and voids in the insulation, and soffits were also a problem area for installation. On one particular wall there were gaps at the top of every second frame cavity. This was probably due to the installer not noticing that the dwangs were staggered, suggesting that the wire probe technique for locating framing was not used or not used properly. It is understood from discussions with installers that the normal practice for Airfoam installers is to mix up one batch of foam in the morning and another batch at lunch time. The area around studs was more sharply defined in the thermal images of one half of the house than in the other, suggesting there was a difference in the shrinkage of the two batches. This was also observed in several other houses. Removal of wall linings would be required to confirm whether this was due to shrinkage differences.

(House C9) *A brick veneer house with clay tiles, insulated in mid-2008*. Again there were a number of areas where insulation was missing and it again appeared that the density of insulation was variable throughout the house. The tops of the walls adjacent to the soffit were not insulated. Although Airfoam installers have said that they are able to pump the foam insulation against the back of this area in the houses where they lift the clay tiles, this is time consuming (hence expensive) and not something they do unless specifically requested by the homeowner. This wall top soffit area is a critical part of the thermal envelope and it appears that it is often missed during installation.

(House W4) *A brick veneer house with building paper, insulated in August 2008.* The thermal imaging showed that the Airfoam installation was inconsistent and poor in many areas of the house. The thermal imaging technique and the use of a videoscope identified some walls where there was very little (if any) urea formaldehyde foam installed at all. This was verified when the wallboards were removed in the living room. The samples collected from the house were poor quality and had many voids throughout the structure of the foam. These samples were used in some of the laboratory tests.

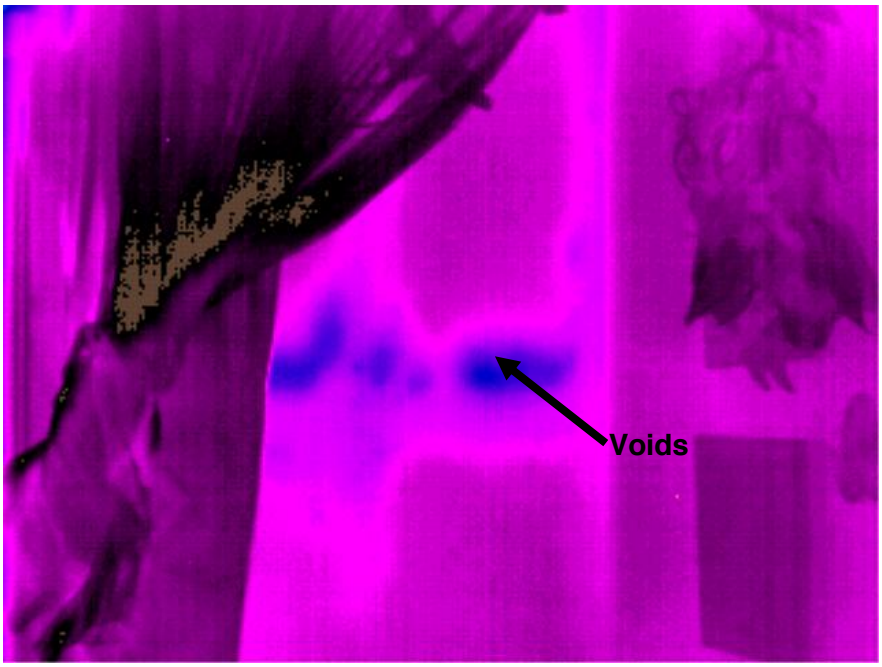

Figure 6: Thermal image showing voids in the Airfoam (House W4)

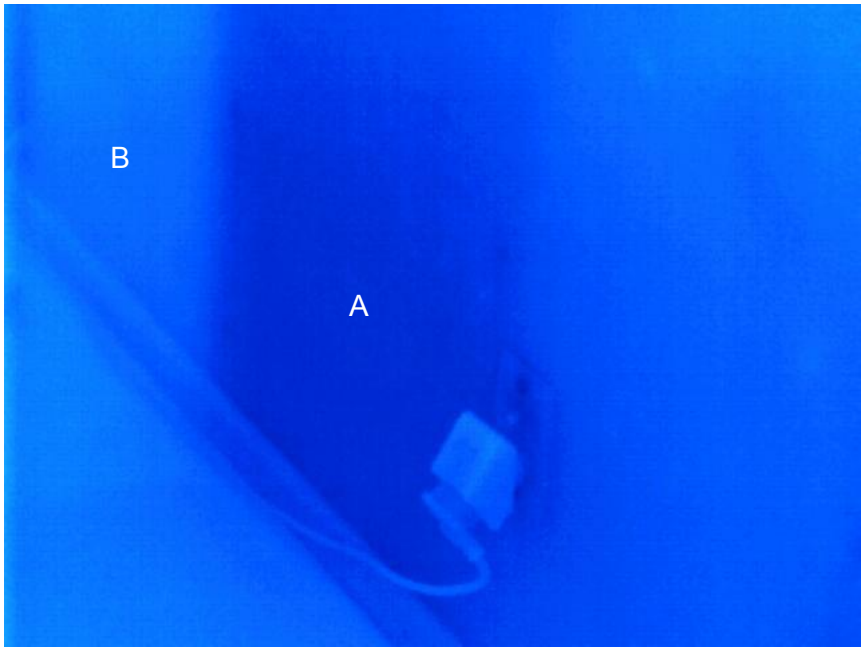

Figure 7: Thermal image indicates no product installed at A compared to B (House W4)

Figure 8: Removal of wallboard confirms missing insulation (House W4)

Figure 9: Airfoam sample removed from wall cavity showing voids (House W4)

(House W3) *A weatherboard / stucco house with building paper, insulated in August 2008.* The thermal imaging again showed that the Airfoam installation was inconsistent in many areas of the house, which was confirmed when some of the wallboards were removed in the bedroom. The samples showed shrinkage from the framing and voids in some areas, which would undoubtedly compromise the thermal performance of the insulation. These samples were used in some of the laboratory tests.

The homeowner stated that the house also had issues with blistering and peeling paint on the weatherboards, as well as a bulging tongue and groove internal lining resulting from the installation of the Airfoam. Some of these issues had since been rectified by the installer. The moisture content of the timber was very high in some places and it was clear the property had some moisture issues unrelated to the installation of the Airfoam insulation. Although the Airfoam was not the main cause of the moisture problems, the high volumes of water evolved during installation processes could have exacerbated the issue.

Figure 10: Removal of wallboard to assess Airfoam installation – note voids present house (House W3)

Figure 11: Removal of wallboard to assess Airfoam installation (House W3)

Figure 12: Blistering paint on weatherboard, evident after Airfoam installation (House W3)

5. LABORATORY STUDIES

A series of laboratory tests have been carried out using appropriate site visit samples and installer-produced samples. These included small scale samples for mechanical and physical property tests, as well as large scale wall samples for evaluating thermal performance of the wall.

5.1 Sample Preparation

Foam samples nominally 550 x 550 x 80 mm were collected by BRANZ during inspection of properties and specimens for the following tests were cut from these samples, while avoiding any significant voids in the foam:

- Plasticiser migration (ASTM D2199) (1 specimen of 100 mm x 90 mm x 30 mm);
- Water absorption (AS/NZS 4201.6) (2 specimens of 100 mm x 80 mm x 40 mm);
- Accelerated aging by thermal and humidity cycling (2 specimens of 90 mm x 60 mm x 70 mm).

The initial sets of new samples were prepared within the BRANZ laboratories by trained Airfoam installers and using the AIRFOAMA apparatus in December 2009.

Two low walls (designated walls C1 and C2) were constructed using H1.2 boron treated framing timber. Wall C1 was faced with timber weatherboards and backed with standard plasterboard. Wall C2 used kraft paper based building underlay behind the timber weatherboards and was backed with standard plasterboard. Each wall comprised 6 studs and UF foam was injected into the cavities between these from the plasterboard side. The two walls were cut to extract smaller framed samples and drying of these small wall sections was confirmed by weighing. These framed samples were used for:

- Accelerated aging, based on the AS 4073 test methodology, to investigate the effects of heat & moisture and compatibility of UFFI with other building components.

The shrinkage of the fully cured UF foam in the remaining cavities of the walls was measured, and samples then cut from the foam for testing for tensile strength (ASTM D1623).

A similar low wall (designated wall D4755) was constructed using H1.2 boron treated framing timber, kraft paper based building underlay, plywood and standard plasterboard. This wall again comprised 6 studs and UF foam was injected into the cavities between these. The weight of these samples was monitored until constant mass indicated that no further drying was taking place. The amount of shrinkage from the framing was measured before the five test specimens (D4755A-E) were removed from the frames and tested using the BRANZ LaserComp Fox 600 heat flow meter apparatus.

Rigid tubes of nominally 200 mm and 150 mm were filled from the top with UF foam to prepare samples. However, as a result of doubts about the influence of the tube on foam shrinkage and the NZS 4235 requirement that the tubes be filled from the bottom to minimise air entrapment, further samples were prepared in February 2010 once a robust sample preparation methodology had been agreed between BRANZ and the Airfoam installers.

A large scale wall (designated wall D4861) was constructed using H1.2 boron treated framing timber, kraft paper based building underlay, timber weatherboards and standard plasterboard with face dimensions 2.4 m wide by 2.4 m high and thickness of approximately 120 mm. Studs were set at 600 mm centres and dwangs at 800 mm.

UF foam was injected into the insulation cavities, behind the building underlay, from the outside, using holes drilled through the weatherboard by an Airfoam applicator in December 2009. The specimen was then stored in the BRANZ laboratory for five weeks until being tested in mid January 2010 (Figure 13 and Figure 14).

As a demonstration of the effects that shrinkage gaps can have on the thermal performance, a further 2.4 m by 2.6 m panel was constructed (designated wall D4862) and tested that was identical to the first except an R 2.8 glasswool insulation product was used instead of Airfoam. In the first of two tests (D4862a) with the panel the insulation was well fitted without gaps, whereas for the second test (D4862b) gaps representing 6% of the insulation width were deliberately created at the sides (3% either side) and top (6%) of each frame cavity. However unlike the Airfoam panel, which was expected to have shrinkage gaps between the face of the insulation and the inside face of the cladding and lining, gaps were only created around the edges of the glasswool and not against the faces (shown in Figure 17 to Figure 21).

Figure 13a & b: Installation of Airfoam in large scale test wall (D4861) at BRANZ

Figure 14: Test wall (D4861) after Airfoam installation and plasterboard removed

It should be noted that during the Airfoam installation at BRANZ, thermal imaging was used to evaluate the installation process. In some cases the installation of the foam was found to be unsatisfactory. For optimum results the thermal imaging analysis should be carried out post installation of the Airfoam and not during the installation process.

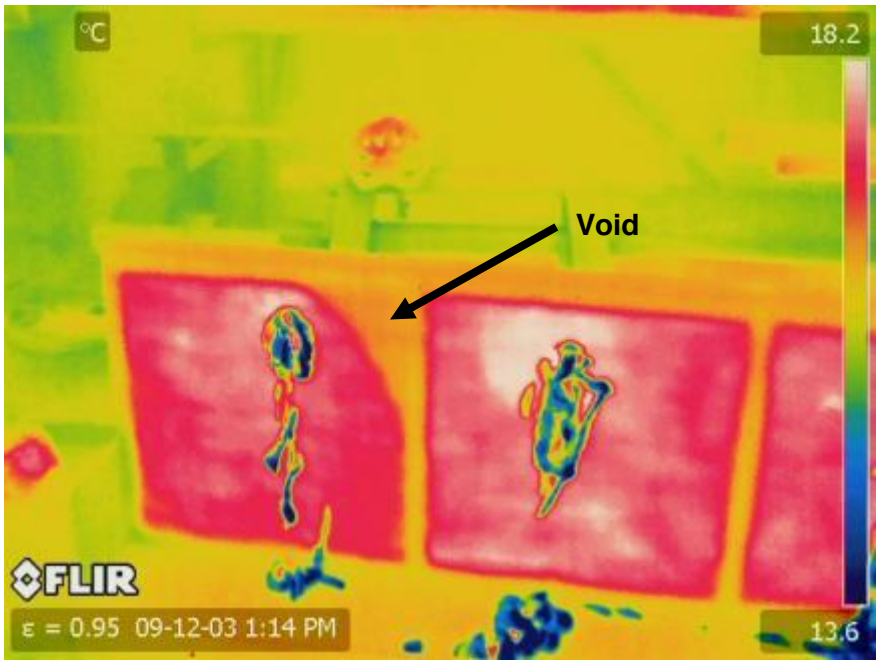

Figure 15: Thermal image indicating poor installation of Airfoam within test samples (D4755A)

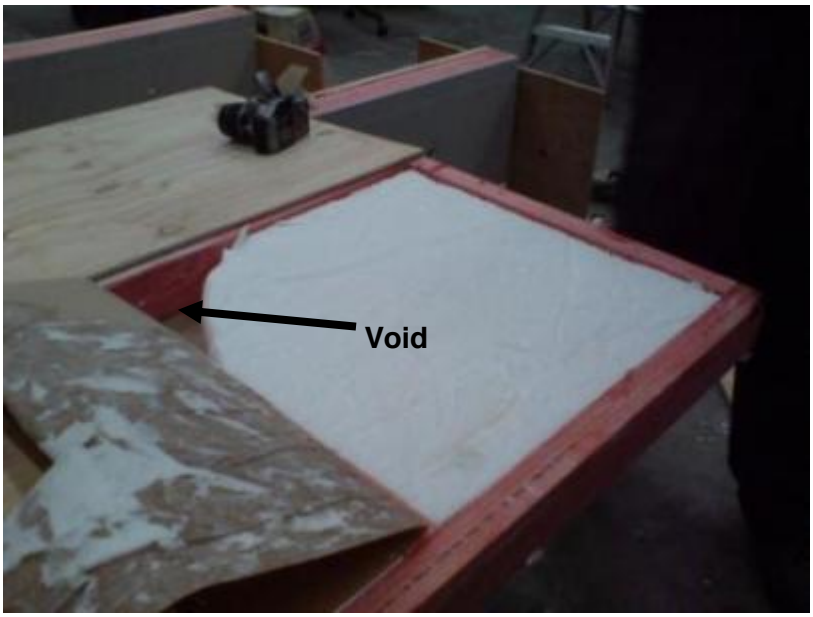

Figure 16: Confirmation of poor installation (D4755A)

Figure 17 & 18: Thermal images of panel (D4861) immediately before thermal testing

Figure 19 & 20: Frame before insulation (D4862) and with well fitted R 2.8 glasswool insulation (D4862a)

Figure 21: R 2.8 glasswool insulation fitted with 3% gaps at side and 6% gap at the top of each frame cavity (D4862b)

Further new samples were prepared within the BRANZ laboratories by trained Airfoam installers and using the AIRFOAMA apparatus in February 2010.

Another low wall (designated wall D4865) was constructed using H1.2 boron treated framing timber, kraft paper based building underlay, plywood and standard plasterboard. As before, this wall comprised 6 studs and UF foam was injected into the cavities between these. After drying, the foam samples were retained for future testing, if required.

Rigid tubes of nominally 200 mm and 150 mm were filled from the bottom with UF foam, as required by the NZS 4235 standard. Samples for the following tests were extracted from these:

- Shrinkage (NZS 4235/BS 5617);
- Density (ASTM D1622 & NZS 4235/BS 5617).

A further wall (D4863) was constructed using 2.4m x 2.6m flat panels with 95mm x 45mm H3.1 timber frames clad with red Monier 90 series bricks on a stepped concrete foundation to give a 40mm weathertightness cavity. The wall was constructed with galvanised brick ties and weep holes at appropriate intervals.

The wall sample (D4863) had a layer of black kraft paper installed against the cavity face of the framing and standard 10 mm plasterboard fixed to the other face (Figure 22). UF foam was injected into the insulation cavities, behind the building underlay, from the outside, using holes drilled through the mortar joints of the brick veneer by an Airfoam applicator on 12 February 2010. The specimen was then stored in the BRANZ laboratory for seven weeks until being tested for thermal performance in the Guarded hotbox from 1 to 14 April 2010.

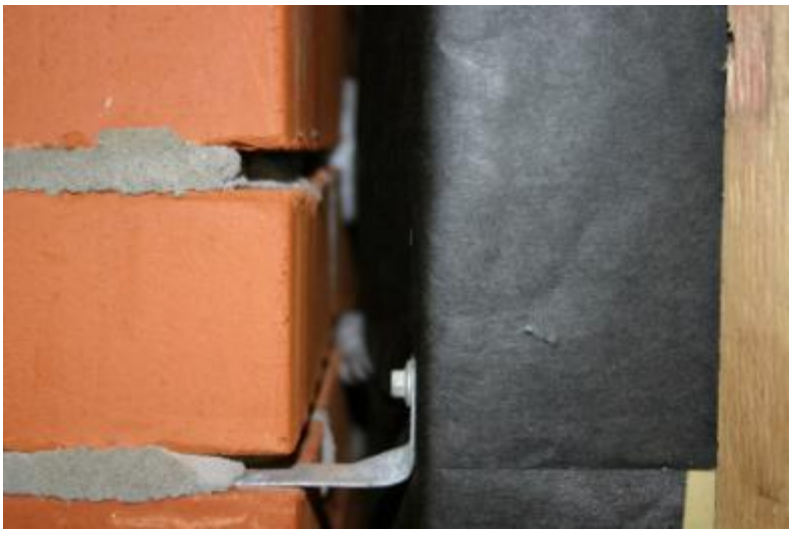

Figure 22: Cavity of Brick Veneer Wall (D4863a)

After the thermal testing, the plasterboard lining was removed from the UFFI-insulated brick veneer wall (D4863a). The UFF insulation was observed to have shrunk approximately 6% (Figure 23). It should also be noted that within one panel the UFF insulation was incomplete, resulting in a larger void. One further observation was that the installation of the UFFI caused bulging of the kraft paper and in some areas was in contact with the brick veneer.

The foam insulation was then replaced with an R 2.8 glasswool insulation product and the wall retested for thermal performance (D4863b). Finally the glasswool insulation was removed and the wall was re-tested without any insulation.

Figure 23: UFF-insulated brick veneer wall (D4863a) with plasterboard removed

5.2 Test Methods and Results

5.2.1 Plasticiser migration (ASTM D2199)

The method described in ASTM D2199 was adapted to examine the migration of plasticiser from the UF foam sample and from a control polystyrene foam sample. A block, nominally 100 mm x 90 mm x 30mm, was cut from each material. A section of PVC insulated cable, a piece of plasticiser-containing polyurethane sealant and a length of PVC tape (wrapped around a small weight) were placed on top of each of the foam blocks and the assemblies placed in an oven at 50°C for 60 days. After exposure a visual assessment of the extent of sticking of each plasticised material to the foam block was completed.

A UF foam sample was extracted from material collected from one of the inspected properties. After 60 days in the oven at 50°C neither the PVC insulated cable, the plasticiser containing polyurethane sealant nor the length of PVC tape showed any signs of sticking to the UF foam sample collected during the inspection of properties. Meanwhile, the PVC insulated cable and PVC tape were firmly stuck to the polystyrene foam. The plasticiser-containing polyurethane sealant had sunk into the polystyrene foam as a result of migration of plasticiser.

5.2.2 Water absorption (AS/NZS 4201.6)

Testing was carried out generally following the method of AS/NZS 4201.6. Two samples, nominally 100 mm x 80 mm x 35 mm, were cut from the UF foam, weighed and completely immersed in water for 24 hours. The weight of the samples was then re-measured.

UF foam samples were extracted from material collected from one of the inspected properties. The sample dimensions and dry density are reported in Table 1.

Sample	Dimension (m)			(m^3)	Dry weight (g)	Density (g/m^3)
1	0.103	0.082	0.036	0.0003	2.54	8353.7
2	0.096	0.08	0.035	0.00027	2.23	8296.1

Table 1: Sample dimensions and density before soaking

The sample dry weight, the soaked weight and the water absorbency are reported in Table 2.

Sample	Dry weight (g)	Soaked weight (g)	Soaked grammage (g/m^3)	Water absorbency (g/m^3)
1	2.54	22.79	74953.3	66599.6
2	2.23	16.38	60937.5	52641.4

Table 2: Soaked weight and the water absorbency

The results indicate that the material is an open-cell foam, as a large quantity of water has been quickly absorbed.

5.2.3 Shrinkage

The dimensions of the fully cured UF foam in the cavities of the low walls designated C1 and C2 were also measured. The shrinkage of the samples from the rigid tubes prepared in February 2010 was measured following NZS4235 / BS5617. An average linear shrinkage of 8.97% was obtained on samples with an effective density of 11.86 kg/m^3.

Figure 24: : Shrinkage in low wall C1, specimen C1D.

The nominal dimensions of the cavities, into which the foam was injected, were nominally 600mm x 600mm x 90 mm and the shrinkage of the foam derived from these dimensions is reported in Table 3.

Specimen	C1A	C1D	C2A	C2B	C2D	Mean / mm	Shrinkage / %
Length / mm	565	565	565	565	565	565	5.8
Height / mm	560	570	570	570	570	569	5.2
Depth / mm	85	85	85	85	85	85	5.5

Table 3: Shrinkage in low wall samples

5.2.4 Tensile Strength (ASTM D1623)

Testing was completed following ASTM D1623. Twenty specimens, each nominally 50 mm x 50 mm x 50 mm, were cut from UF foam removed from test wall C1 (see section 5.1), specimen C1B.

Aluminium dollies of a dimension 50 x 50 mm were glued to opposing surfaces of each sample with epoxy resin. Following conditioning at 22°C and 50% RH for 48 hours, an Instron 5569 Universal Testing Machine with a 10kN load cell was used to test the samples in tension.

Results were recorded for 17 specimens at a cross-head speed of 1 mm/min, the three other samples prepared failed in shear while mounting in the test equipment. The results are reported in Table 4 and the significant variation in tensile strength demonstrates the variability of the product.

Specimen No.	Peak Load (N)	Tensile Stress (kPa)
1	9.5	3.8
2	5.6	2.2
3	36.9	14.8
4	5.8	2.3
5	7.9	3.2
6	36.9	14.8
7	23.1	9.2
8	13.5	5.4
9	14.9	6.0
10	2.2	0.9
11	9.2	3.7
12	2.2	0.9
13	22.3	8.9
14	19.1	7.6
15	6.0	2.4
16	7.5	3.0
17	21.8	8.7
Mean	**14.4**	**5.8**
S.D.	**10.9**	**4.3**

Table 4: Tensile Results

5.2.5 Water Vapour Transmission (ASTM E96)

Testing was carried out following ASTM E96 Method B. Four samples were cut from UF foam from the tubes filled during December 2009.

Two samples were cut from the bulk of the foam (Samples 303a & 303b) and two samples were cut so that they used an outer face of the dried foam exposed to the test container (Samples 303c & 303d).

The vapour permeability of the samples was determined by monitoring the mass of the samples for 8 days. The results obtained are reported in Table 5 and Table 6.

Sample		303a	303b	Mean
Weight change (g)		32.260	35.598	
Rate of weight change (g/d)		3.670	4.049	3.860
Vapour flow	g/m²d	393.320	434.017	413.669
R	MNs/g	0.279	0.253	0.266

Table 5: Water vapour transmission from bulk samples taken from tubes filled during December 2009

Sample		303c	303d	Mean
Weight change (g)		35.343	34.176	
Rate of weight change (g/d)		4.020	3.888	3.954
Vapour flow	g/m²d	430.908	416.680	423.794
R	MNs/g	0.255	0.264	0.259

Table 6: Water vapour transmission from surface samples taken from tubes filled during December 2009

5.2.6 Accelerated aging by thermal and humidity cycling

BRANZ examined the shrinkage of the UF foam after exposure to cyclic temperature / humidity. UF foam samples were extracted from material collected from one of the inspected houses (W3). Samples nominally 90 mm x 60 mm x 70 mm were cut and accurately measured. The samples were exposed to 30 repeats of a temperature and humidity cycle as defined in Table 7. The cycle was chosen to mimic the temperature and humidity extremes experienced in-service.

Period (h)	Temperature (°C)	Relative Humidity (%RH)
6	30 ± 3	90 ± 5
6	60 ± 3	75 ± 5
6	10 ± 3	50 ± 5
6	-10 ±3	Low RH

Table 7: Temperature and Humidity Cycle

The dimensions of the samples were re-measured after equilibration under ambient conditions.

The dimensions of the samples before and after thermal and humidity cycling are detailed in Table 8.

Sample		Dimensions (m)			(m^3)
1	Control	0.092	0.057	0.072	0.00038
1	Cycled	0.086	0.056	0.069	0.00033
2	Control	0.095	0.064	0.074	0.00045
2	Cycled	0.083	0.063	0.072	0.00038

Table 8: Sample dimensions before and after temperature and humidity cycling

The percentage change for each sample as a result of the thermal and humidity cycling are detailed in Table 9.

Sample	Dimensional Shrinkage (%)			Volume Shrinkage (%)
1	6.5	1.8	4.2	12
2	12.6	1.6	2.7	16.3

Table 9: Sample shrinkage as a result of temperature and humidity cycling

The results indicate that there is potential for further shrinkage of installed and dry UF foam material if subjected to thermal / humidity cycling and that this potential additional shrinkage will vary in the different directions within the wall. Since the results indicate further shrinkage is possible, additional work was completed on Airfoam-prepared samples, as described in Section 5.2.7. Scanning electron microscope (SEM) images of the cell structure of the foam pre- and post aging are shown in Figure 25 and Figure 26

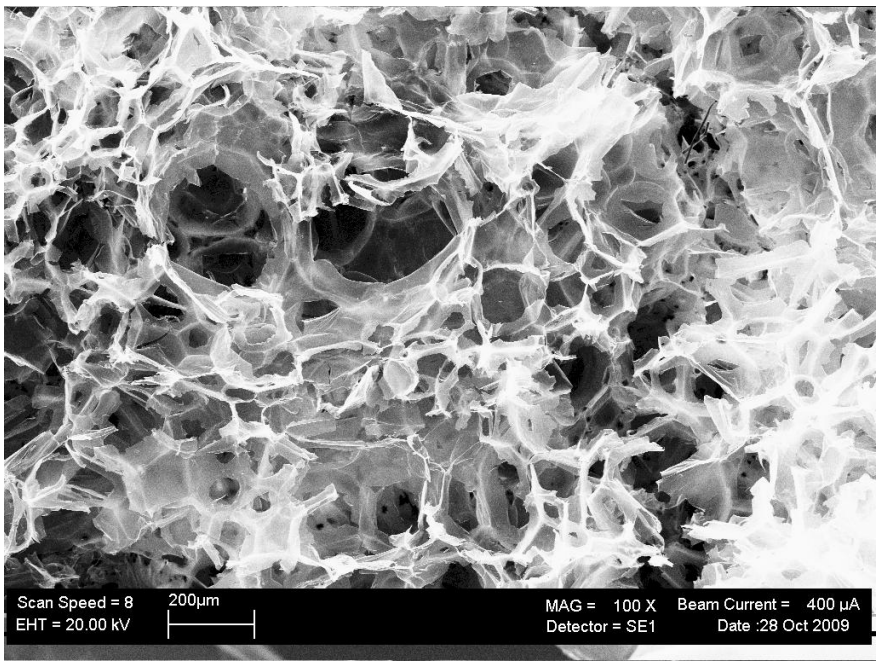

Figure 25: SEM of Airfoam sample removed from House W3

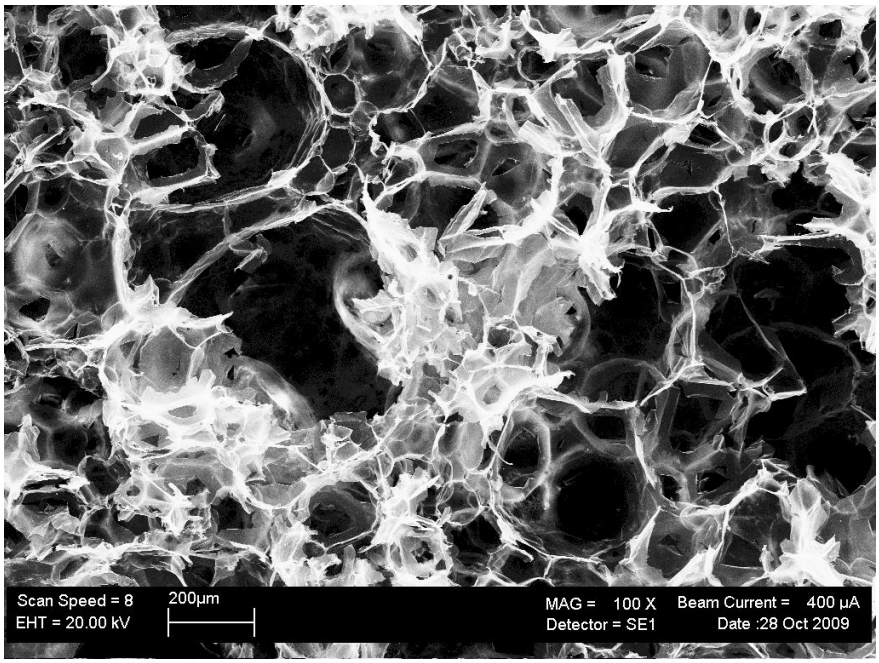

Figure 26:SEM of Airfoam sample from House W3 after accelerated aging, showing collapsing of foam structure

5.2.7 Accelerated aging by temperature and humidity

BRANZ examined the shrinkage of the UF foam after exposure to 50°C and 96% RH as detailed in AS 4073-1993 Appendix H Shrinkage of Dry-Set Foam at Elevated Temperature and Humidity.

Fully cured UF foam within the cavities of the low wall samples designated C1E and C2C were aged at 50°C and 96% RH in a Contherm climate cabinet. The samples were aged for 28 days and then dried at 40°C for 24 hours. Fully cured UF foam within the cavities of the low wall samples designated C1A and C2A were stored in the laboratory under ambient conditions to act as control samples.

The dimensions of all samples were re-measured after equilibration under ambient conditions. Figure 27 shows a photo of sample C1E after aging along with control sample C2A.

Figure 27: Shrinkage in low wall specimen C1E (left) after aging following 'AS 4073-1993 Appendix H' compared to control specimen C1A

The dimensions of the samples before and after thermal and humidity cycling are detailed in Table 10.

	Controls		Aged		Mean Change / mm	Shrinkage / %
Specimen	**C1A**	**C2A**	**C1E**	**C2C**		
Length / mm	565	565	540	550	20	3.5
Height / mm	560	570	535	535	30	5.3
Depth / mm	85	85	80	80	5	5.9

Table 10: Sample dimensions before and after temperature / humidity aging and shrinkage results

The results confirm that there is potential for further shrinkage of installed and dry UF foam material if subjected to elevated temperatures / humidity during service. The AS4073-1993 Table 1 'Properties of Set Foam' requires a maximum shrinkage of 4% at elevated temperature and humidity. The results for the Airfoam-prepared samples (Table 10) indicate that the product does not satisfy these requirements. Samples were examined using scanning electron microscopy (SEM) to inspect the cell structure of the foam. The results further supported earlier work by CSIRO,[11] which demonstrated that the UF foams collapse under high humidity conditions and potentially emit formaldehyde as the foam structure breaks down. Images of a control sample and a sample aged following the procedures of AS 4073-1993 Appendix H are shown in Figure 28 and Figure 29.

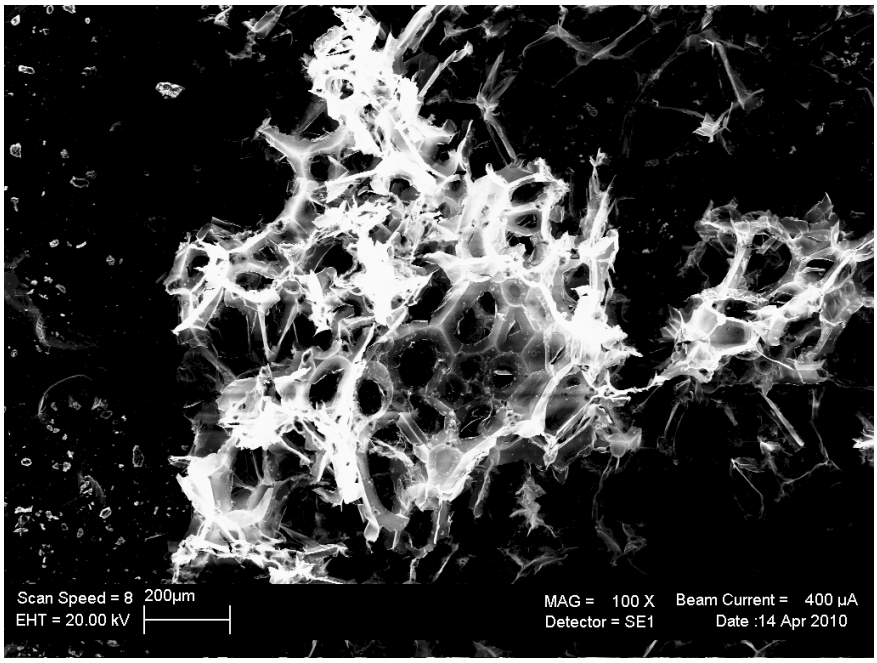

Figure 28: SEM of Airfoam sample C1A

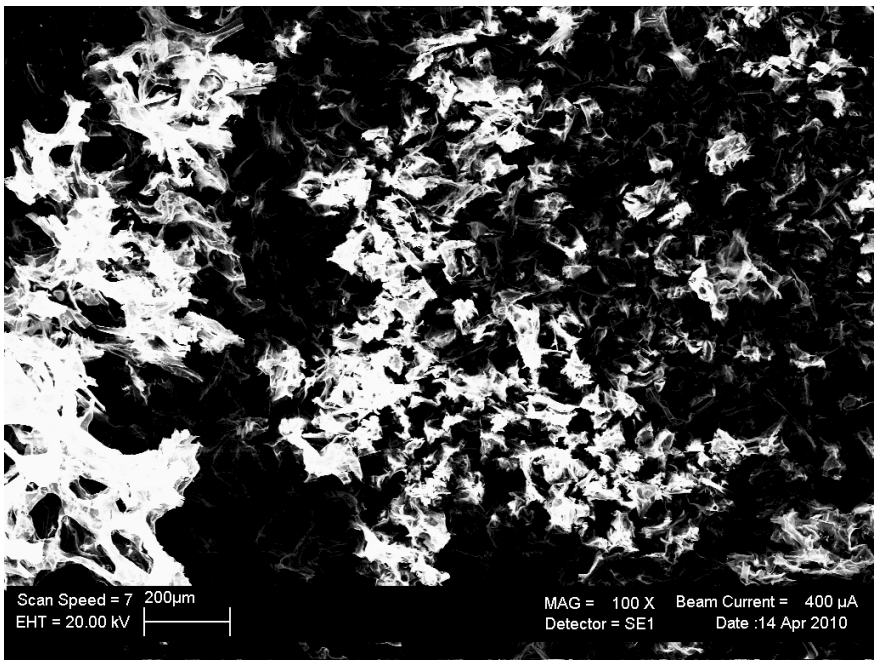

Figure 29: SEM of Airfoam sample C1E after accelerated aging, showing collapsing of foam structure

5.2.8 Thermal Conductivity of the Foam Material (ASTM C518)

The test equipment used was a LaserComp Fox 600 heat flow meter. The specimen for testing was placed horizontally in the apparatus, with upwards heat flow. The hot and cold plates each have a 250 mm x 250 mm heat flux transducer embedded in their surface. The edges of the specimen are insulated from the room ambient temperature. These measurements comply with the requirements of ASTM C518. The uncertainty in the measurements of thermal conductivity and thermal resistance is estimated to be ± 3%.

Airfoam claims an R-value of 2.9 per 100 mm thickness of foam (conductivity 0.034 W/mK) and also that the linear shrinkage of the material is 6%. The US National Bureau of Standards publication NBS Technical Note 1210, March 1985 notes that shrinkage of Urea-Formaldehyde foam has been observed as being as high as 10% and notes that even at only 6% shrinkage the laboratory determined thermal resistance of R 2.8 per 100 mm thickness (conductivity 0.036 W/mK) should be de-rated by 30% to R 2.0 (conductivity 0.050 W/mK) to account for the volume of material lost through that shrinkage.[37] The Technical Note quotes from a 1978 US Federal Trade Commission (FTC) review of UF-foam; 'The claimed R-value must be based on reliable scientific proof of the extent of shrinkage and of its effect on R-value, otherwise the manufacturer is required to disclose that the shrinkage may significantly reduce the R-value'.

For the BRANZ testing samples produced in December (D4755 A-E), the shrinkage was approximately 6% and the density 11.5 kg/m^3. One of the samples was removed from the timber frame and dried for 24 hours at 45 °C. No further weight loss or shrinkage occurred. Measured thermal resistance using the heat flow meter (Table 11) was approximately R 2.5 per 100 mm (conductivity 0.040 W/mK), so a 30% de-rating to account for 6% shrinkage gives a theoretical installed R-value for the material of R 1.75 per 100mm (conductivity 0.057 W/mK). The effects of shrinkage were investigated in more detail and the results are outlined in section 6.2.8.

It should be noted that the density of the product varies significantly, as shown from the measurements taken of samples produced by Airfoam at BRANZ and those taken from the site visits. Earlier samples taken from house inspections (W3 and W4) were at a density range of approximately 6 to 8 kg/m^3 and gave R-values of R 1.05 and R 1.7 per 100 mm, but those samples contained noticeable quantities of voids and air-bubbles. As noted above, the Airfoam-prepared samples produced in December (D4755 A-E), had a density 11.5 kg/m^3.The foam in the weatherboard and brick veneer panels used for Guarded Hotbox testing (Section 5.2.9) was at a slightly higher density of 13.2 and 13.8 kg/m^3 respectively with noticeably less voids and air bubbles. The Airfoam website gives a density range for the product of 8 to 13 kg/m³.

Test Specimen (BRANZ reference number)	Thermal Conductivity (W/mK ± 3%) @ 15°C and density of 11.5 kg/m^3
D4755A	0.0380
D4755B	0.0431
D4755C	0.0420
D4755D	0.0383
D4755E	0.0396
Average	**0.040**

Table 11: Thermal conductivity measurement results

The range in results of 13% (Table 11) is reflective of the variation in texture with some samples having more voids than others.

Based on these results, the estimated R-value for a material thickness of 90 mm (density 11.5 kg/m^3) is 2.2 m^{2}K/W excluding shrinkage and 2.1 m^{2}K/W assuming shrinkage of 6% (thickness 84.6 mm). The estimated R-value for a material thickness

of 100 mm is 2.5 m^2K/W excluding shrinkage and 2.3 m^2K/W assuming shrinkage of 6% (thickness 94 mm).

The thermal conductivity represented by the Airfoam claim of R 2.9 m^2K/W for 100 mm thickness of foam (www.airfoam.co.nz) is 0.0345 W/mK which is approximately 14% lower than the average thermal conductivity measured here.

5.2.9 Thermal Performance of Wall Specimen (ASTM C1363)

The thermal performance test for an Airfoam insulated wall was carried out using the BRANZ Guarded Hot Box (GHB), which consists of two insulated chambers of approximate face area 2.4 m x 2.4 m, with an internal depth of 1.2 m. The apparatus is constructed and operated according to ASTM C1363-97. The final R-value is determined by averaging the measurements over at least 24 hours (See Appendix 7.2 for further details).

Figure 30: Guarded Hot Box

The wall panel test results are recorded in Table 12.

Test Panel	**Airfoam insulation weatherboard**	**R2.8 Glasswool well fitted weatherboard**	**R2.8 Glasswool 6% gaps weatherboard**	**Airfoam insulation brick veneer**	**R2.8 Glasswool well fitted brick veneer**	**Un-insulated brick veneer**
Sample number	**D4861**	**D4862a**	**D4862b**	**D4863a**	**D4863b**	**D4863c**
Test period	8th to 12th Jan	12th to 19th Jan	20th to 23nd Jan	1st to 8th Apr	9th to 13th Apr	13th to 14th Apr
Temperature stabilisation (days)	2	2.5	1	4	2	0.5
Test interval after temp. stability achieved (days)	2.5	4.5	2	3	2	0.5
Approx. mean sample temp. (°C)	23	23	23	23	23	23
Approx. cold side air temp. (°C)	13	13	13	13	13	13
Approx. warm side air temp. (°C)	33	33	33	33	33	33
Air-to-air temp. difference (K)	19.35	19.41	19.29	19.65	19.59	19.20
Heat flux (W/m^2)	15.00	8.37	12.53	11.77	7.45	32.00
Measured air-to-air thermal resistance (R-value) m^2K/W ± 10%	1.29	2.32	1.54	1.67	2.63	0.60
Foam density after testing (kg/m3)	13.2			13.8		
Average shrinkage of foam (height & width)	6%			5.5%		
Air-to-air R-value (m^2K/W ± 10%) when adjusted to a mean temperature of 15°C	**1.4**	**2.4**	**1.6**	**1.8**	**2.7**	**0.7**

Table 12: Wall panel test results

The GHB test method requires that there is no air exchange into or out of the test specimen so for the testing of the brick veneer sample it was necessary to block the weep holes at the bottom of the wall. In reality the cavity behind brick veneer is considered a ventilated cavity and the R-values are lower than calculated on the basis of an unventilated airspace. The actual R-value of the brick walls is expected to be approximately R 0.4 lower than the values measured using the GHB.

5.2.10 Thermal Modelling

Finally 3-D finite element modelling was then used as a check of the thermal resistance measurements. The tested panels were modelled using HEAT3, a three dimension finite element heat transfer modelling software package.[38] The Airfoam panel was modelled for various shrinkage gaps between none and 8% using the average thermal conductivity of the five test specimens measured using the heat flow meter apparatus.

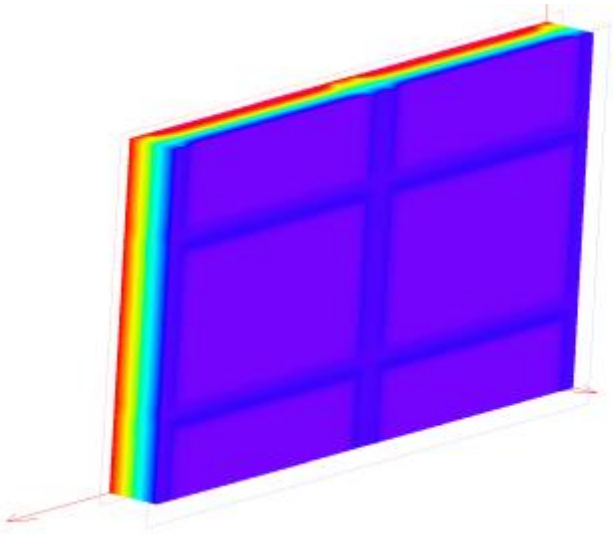

Figure 31: Example image from 3D model (colour indicates temperature)

Insulation (wall panel with14% framing ratio)	Model thermal resistance m^2K/W	Impact from shrinkage / gaps	Measured thermal resistance m^2K/W
Airfoam without shrinkage 90mm framing (material R-value 2.5)	2.13		
Airfoam 2% shrinkage	1.78	-16%	
Airfoam 4% shrinkage	1.59	-25%	
Airfoam 6% shrinkage	**1.45**	-32%	**1.4**
Airfoam 8% shrinkage	1.34	-37%	
R 2.8 Glasswool without gaps	**2.42**		**2.4**
R 2.8 Glasswool with 6% gaps	**1.60**	-34%	**1.6**
Airfoam without shrinkage 100mm framing (material R-value 2.5)	2.32		
Airfoam 6% shrinkage 100mm framing	1.55	-33%	
Airfoam without shrinkage assuming 100mm deep frame and material R 2.9 at 100 mm thickness (see below) (conductivity 0.0345 W/mK)	2.53		
Airfoam with 6% shrinkage assuming 100mm deep frame and material R 2.9 at 100 mm thickness before shrinkage (see below)	1.63	-36%	

Table 13: Modelling and measured results

The best fit with the measured result for the Airfoam panel is with the model for 6% shrinkage. 6% shrinkage is what has been observed with the test sample created for the heat flow meter measurements. The model for the R 2.8 m^2K/W glasswool insulation with 6% gaps is a perfect fit with the results measured for the test panel with 6% gaps. Likewise the model result for the glasswool with no gaps is almost identical to the measured result.

The same thermal resistance result of 1.55 m^2K/W, modelled for the situation of the Airfoam material (same conductivity as measured here) in a 100 mm deep frame cavity (14% framing ratio) with 6% shrinkage by modelling, is obtained for an R 1.28 m^2K/W material (conductivity 0.078 W/mK) in the same frame without shrinkage. The insulation material would therefore be working approximately half as effectively as the nominal R-value of the material without shrinkage (R 2.5 m^2K/W) would suggest.

Likewise, the same thermal resistance result of 1.63 m^2K/W, modelled for the situation of an R 2.9 m^2K/W material in a 100 mm deep frame cavity with 6% shrinkage, is obtained by modelling for an R 1.41 m^2K/W material (conductivity 0.071 W/mK) in the same frame without shrinkage. Again, the insulation material would be working half as effectively as the nominal R-value of the material without shrinkage.

A realistic best case weatherboard clad wall in terms of shrinkage would have a 10% framing ratio (studs at 450 mm centres and no dwangs) and a frame depth of 100mm. Modelling that situation gives a thermal resistance for the system of R 2.46 m^2K/W without shrinkage and R 1.84 m^2K/W when shrinkage of 6% is included. In that situation the insulation material would yield modelled results equivalent to R 1.61 m^2K/W.

There is good correlation between measurement and models indicating that where there are gaps due to shrinkage of Airfoam insulation the system thermal performance can be predicted and explained by the missing insulation associated with those shrinkage gaps.

For a 100 mm framing depth the thermal resistance is estimated to be approximately 10% greater. Likewise for framing ratios other than the 14% used for these measurements and modelling the thermal resistance will be slightly different because of a different proportion of thermal bridging from framing and shrinkage.

Airfoam asserts on its website www.airfoam.co.nz an R-value of 2.9 m^2K/W per 100 mm thickness of foam but is not clear if that includes the effects of shrinkage. The website states that '*Airfoam will not slump or sag with the wall cavity*'. Technical information on the website states the shrinkage as:

6.5% (BS 5617); 6.6% (BKS); 3.8% (DIN 18159. part 2); 3.0% (HUD U. of M. Bull. No.74).

As mentioned in Section 5.2.8, the NBS Technical Note 1210 published 25 years ago states that shrinkage of UF foam has been observed as being as high as 10% and in such cases the thermal resistance should be de-rated. [37]

The thermal conductivity of Airfoam has been measured as 0.040 W/mK at 15°C, which corresponds to a nominal material thermal resistance of 2.5 m^2K/W in a 100 mm frame cavity (excluding the effects of shrinkage). Including 6% shrinkage the insulation material is expected to perform in a typical frame cavity as if it has a material R-value of R 1.28 m^2K/W. This is almost half the nominal value, and 45% of the R 2.9 m^2K/W material value claimed by Airfoam. Even for the best case situation of studs at 450mm centres and no dwangs the material is expected to be equivalent to R 1.6. m^2K/W.

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7. APPENDIX 1

7.1 Airfoam Technical Information*

Density	8 to 13 kg/m³ (BS 4370)
Thermal Conductivity (k Value)	0.030 W/mK at 5°C (BS 874)
	0.032 W/mK at 20°C
	0.034 W/mK at 30°C
	(after conditioning at 23°C, 65% r.h.)
	0.032 W/mK at 20°C
	(after conditioning at 23°C, 95% r.h.)
Shrinkage	6.5% (BS 5617)
	6.6% (BKS)
	3.8% (DIN 18159. part 2)
	3.0% (HUD U. of M. Bull. No.74)
Water Absorption	0.65 kg/m² (BS 5617)
	2.0% vol.% (DIN 18159. part 2)
Water Vapour Permeability	μ = 1.7 to 3.4 (BS 4370)
Physical Structure	Completely open-celled (BS 4370)
Compression Strength	16 kPa (BS 4370)
Electrical Insulation Resistance	2.9 x 1012 ohms (ASTM D-257)
Flammability	Extent of burning (ASTM D1692)
Limiting Oxygen Index	29% (ASTM D-2863)
Smoke Density	Less than 5% (BS 5111)
Flash Ignition Temperature	402°C (ASTM D-1929)
Self Ignition Temperature	621°C (ASTM D+1929)
Energy Balance	1 sq. metre of standard cavity
Energy content of Airfoam	-40 MJ
Typical Energy saving	-210 MJ per annum

Resistance to Microbial Attack Immune to attack from Merulius lacrymans (dry rot fungus). Poria monticola (pore fungus). Coniophora cerebella (cellar fungus). Chaetomium globosum (soft rot fungus). Cladosporium cladosporioides, Paecilomyces variotti, Penicillium expansum, Stachybotrys atra, Aspergillus niger (BKS. BS 1982).

** Technical information from Airfoam website (www.airfoam.co.nz)*

7.2 Guarded Hotbox Information

7.2.1 Apparatus

- Two insulated, open faced, temperature controlled chambers plus associated external heating and cooling equipment
- A large diameter, slow rotation, mixing fan in each chamber
- Insulated heat flow metering box (meter box) including DC electrical heating elements and circulation fans
- Precision programmable power supply for driving of metering box fans and measurement of their power consumption
- Precision programmable power supply for heating the metering box and measurement of the heating power
- 25 element thermopile imbedded into the interior and exterior surfaces of the walls and back face of the meter box
- 16 pairs of type 'T' thermocouples for measuring the air-to-air temperature difference between the two chambers
- 2 sets of 16 pairs of type 'T' thermocouples for measuring the air-to-surface temperature difference on the faces of the test specimen
- PC based data acquisition and control system with sampling every 5 seconds and data recording at 1 minute intervals.

7.2.2 Chambers

The test apparatus was the BRANZ Guarded Hot Box which consists of two insulated chambers of approximate face area 2.4 m x 2.4 m, with an internal depth of 1.2 m. The four sides and one face of the chambers include 100 mm of rigid foam insulation (R 2.6 m^2K/W). The open faces of the chambers are held against the faces of the test specimen. The test specimen was sandwiched between the faces of the two chambers. The temperature of the air in the two chambers is controlled independently using heating and cooling equipment which is connected to the chambers using 300 mm diameter supply and extract ducts on opposite sides of each chamber. There is also a large diameter, slow rotation, mixing fan in each chamber.

7.2.3 Meter Box

One chamber is kept warmer than the other so that there is a constant temperature difference across the test specimen, generating a constant heat flow, which is measured using a 1.2 m x 1.2 m face area metering box. The 2.4 m x 2.4 m dimensions of the test specimens allows for a so called 'guard' area of at least 600 mm between the edges of the meter box and the perimeter of the specimen. The guard area minimizes lateral heat flow in the test specimen near the metering area. The meter box has a depth of 240 mm including 50 mm of rigid foam insulation (R 2.0 m^2K/W) on all four sides and the back face. The front face is open and is kept against the face of the specimen under test.

Inside the meter box there are DC electrical heating elements and mixing fans. Fans and baffles within the meter box produce air movement in one direction against the face of the sample. Imbedded into the surfaces of the four sides and one face of the meter box is a 25 element thermopile, which gives a null output when the resistive heating power plus fan power supplied to the inside of the meter box is such that the inside surfaces are being maintained at exactly the same temperature as the outside surfaces. There is then no heat flow through the walls and back face of the meter box

and all of the heating energy is therefore being transferred by air movement through the open front face, and then by conduction through the specimen.

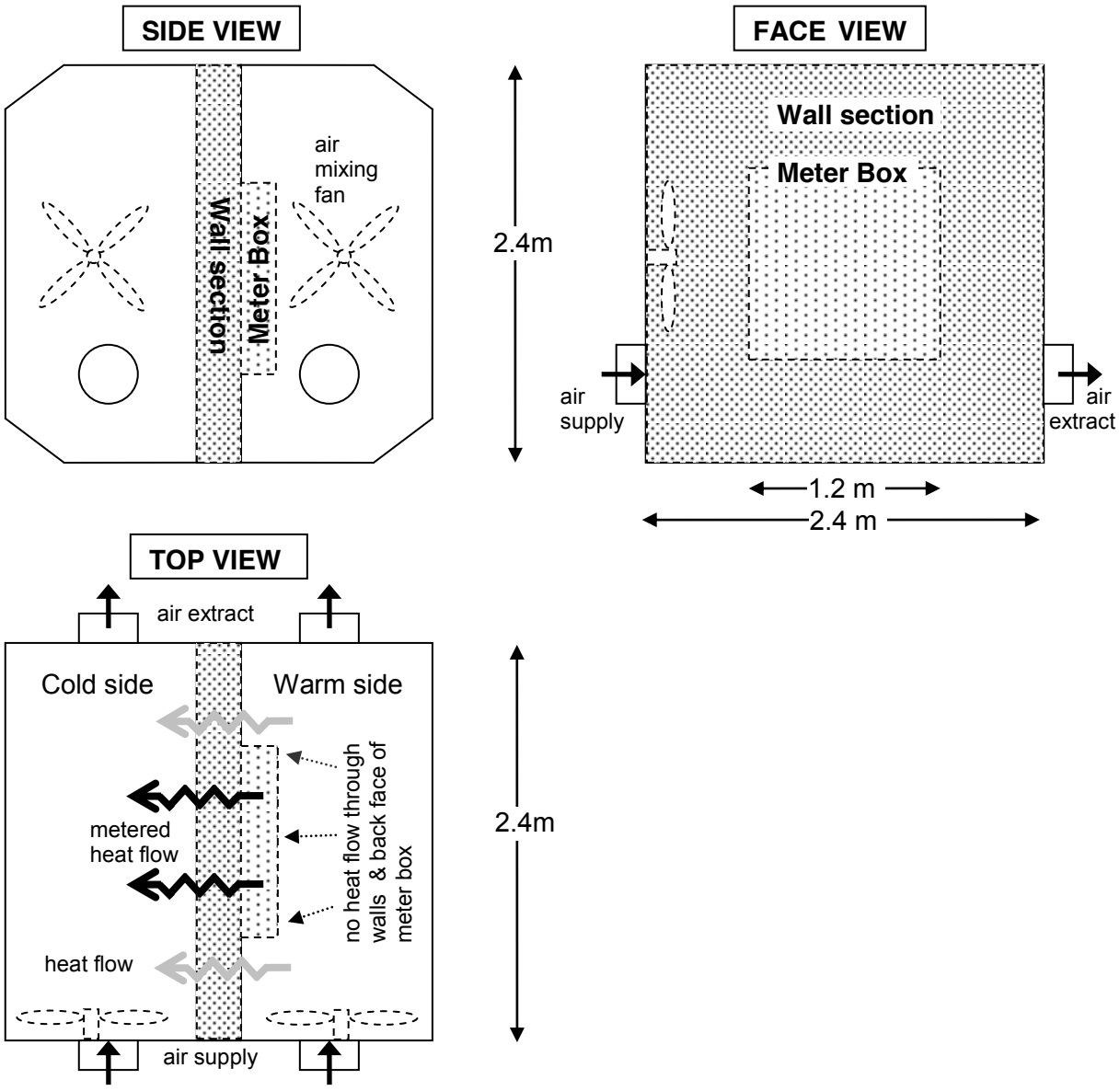

Figure 32: Schematic Diagram of Guarded Hot Box Apparatus

7.2.4 Thermocouples

The air-to-air temperature difference between the two chambers is measured using 16 pairs of type 'T' thermocouples. Air-to-surface temperature differences on both faces of the samples are also measured using two sets of 16 thermocouple pairs. Because the thermocouples form differential pairs, there is no need to measure and include a junction temperature into the determination of temperature difference, leading to increased accuracy and precision above what is normally expected from thermocouple based temperature measurement. All of the thermocouple wire used in association with the apparatus comes from a single batch of wire for which the particular temperature characteristic has been determined.

7.2.5 Method

The apparatus is constructed and operated according to ASTM C1363-97. The test method requires steady-state conditions and therefore does not simulate such effects as the combination of climatic variation and thermal mass. In fact the measurement takes at least three days to allow one day for the initial response to the change in temperature and two days to determine that there were no slow changes in behaviour due to moisture movement in the specimen or exterior environmental effects on the test chambers. The final R-value is determined by averaging the measurements over at least 24 hours. The methodology used within the test did not measure surface air velocities, moisture content or densities of the materials.

The measured total input power to the meter box, including fans, divided by the meter box face area of 1.44 m^2 gives the heat flux in Watts per square metre. The measured temperature difference between the air in the two chambers, divided by the heat flux, gives the air-to-air R-value of the test specimen. The air-to-air R-value includes two air-to-surface resistances which are determined by measuring the difference between the temperature of the air near the surface and the temperature of the surface.

The area measured by the meter box includes two studs (two halves and one full) and two dwangs, so the framing represents approximately 14% of the measured area.