Analysis of the effects of aerogel insulation on the thermal performance of existing building envelopes

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ABSTRACT

Hard-to-treat buildings, dwellings in particular have a significant impact on overall building energy consumption. With approximately five million hard-to-treat dwellings in the United Kingdom, their impact on energy and climate change policy due to their poor energy performance cannot be ignored. This research aimed to develop a solution to reduce the impact of these dwellings by integrating high performance aerogel insulation into the existing hard-to treat building envelope. The suitability of silica aerogel as a potential insulation material for 'hard-to-treat' existing walls was first examined followed by an analysis of the effects of its impact on existing building envelopes' thermal performance. The methods employed in this research involved a combination of field and laboratory testing in order to determine physical properties of the material as well as the suitability of material combinations to form a wall component. Computer simulation software was used to determine the performance of the developed aerogel component on 'hard-to-treat' walls; with the data used to generate the computer simulations being derived from field and laboratory tests. The results of these tests and the subsequent computer simulations have shown that, in many cases, application of the aerogel component satisfies current regulatory requirements for existing walls but also, some of the simulation data suggests benefits with regard to interstitial and surface condensation. In broad terms, the aerogel component has been shown to be significantly advantageous in improving the overall thermal performance of existing 'hard-to-treat' walls.

This research forms the result of a Knowledge Transfer Partnership between Edinburgh Napier University, A Proctor Group Ltd and the Technology Strategy Board, now known as Innovate UK.

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The materials for this research as well as access to laboratory facilities were the result of the author taking part in a Knowledge Transfer Partnership between Edinburgh Napier University, A Proctor Group Ltd and the Technology Strategy Board, now known as Innovate UK.

DECLARATION

I hereby declare that the work presented in this thesis was solely carried out by myself at Edinburgh Napier University, except where due acknowledgement is made, and that it has not been submitted for any other degree.

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NOMENCLATURE

Symbol	**Meaning**	**Unit**
A	Area	m^2
V	Volume	m^3
h	Height	m
l	Length	m
t	Time	t
ρ	Density	kg/m^3
m	Mass	kg
g	Mass flow	$kg/(m^2.s)$
Q	Heat	J
q	Heat flux	W/m^2
Φ	Temperature	^oC
Λ	Thermal conductivity	$W/(m.K)$
R	Thermal resistance	$m^2.K/W$
U	Thermal transmittance	$W/(m^2.K)$
w	Moisture content	u [%]
μ	Vapour resistance factor	--------
Φ	Relative humidity	--------
Ψ	Porosity	--------

CHAPTER 1 INTRODUCTION

This chapter reviews present day energy issues, challenges and prospects for buildings to decrease the energy demand of the UK and in particular potential for retrofitting the current building stock. It also discusses requirements for studies on building materials to improve the energy efficiency of the current building stock and more particularly ‘hard to treat’ buildings, and specifically introduces the potential for aerogel materials and contextualises the current research. It also summarises the problem statement and objectives of the present research and provides an outline of the thesis.

1.1 Energy

Energy; the property of an object or system to do work, this statement very briefly describes a property of nature that humankind has exploited to its advantage on a daily bases since the development of the first stone tools. Our command of this property of nature became an exact science during the dawn of the industrial revolution around the 1760’s with the development of steam driven machinery (*Bottomley, S. 2014*). Our understanding and use of energy over the following two hundred years would see mankind developing methods for energy production ranging from the combustion of hydrocarbons such as coal, oil and natural gas, to nuclear power and more sustainable methods such as fuel cells, geothermal, solar, wind and tidal power, hydroelectricity and biofuels (*McLarty, D. et al. 2015*). Another method of harnessing energy currently under development worth mentioning is nuclear fusion. This technology; according to most estimates is two to three decades away, but if successful it would revolutionise energy production efficiency.

1.1.1 Energy, environment and society

Today, the majority of energy production is achieved by the consumption of a fuel; a hydrocarbon such as those mentioned is section 1.1. The combustion of these hydrocarbons involves the use of oxygen and the resulting chemical reaction creates carbon dioxide, water and heat. The heat produced is used to create steam; the steam drives turbines which turn an armature resulting in the production of an electric current. The carbon dioxide and water vapor produced by power plants using these processes are released into the atmosphere via large hyperbolically shaped cooling towers. This is the point where energy production meets the environment; gasses that have long been shown by science to have insulative properties have being expelled into the atmosphere continuously in extremely large quantities for decades. These gasses; carbon dioxide and water vapor are called greenhouse gasses for this reason. In 1896 a scientist called Svante Arrhenius was the first to claim that fossil fuel combustion would result in global warming (*Arrhenius,1920*). Later in the early 1960's and after several decades of meteorological data had been gathered, scientists such as Wallace Broecker first started to notice minute changes in the mean temperature of the earth's atmosphere; the temperature was gradually rising.

Climatologists have shown with the aid of ice core samples from the Antarctic that the earth's atmosphere has gone through many changes over the last several hundred thousand years, but their data has also shown that the current rise in mean temperature is significantly greater than previous "natural" events (*Kukla et al, 2002*).

Any change in the earth's climate will also have an effect on human society globally. An increase in the earth's mean temperature will eventually result in melting of a portion of the polar ice caps, leading onto higher sea levels which will affect coastal regions globally. In addition, melting of the polar ice caps would in turn increase the fresh water levels of the oceans resulting in a desalination effect, allowing the oceans to increase in temperature thus causing more intense storms.

The extent of forests, grasslands and savannahs would eventually retreat putting greater pressure on native animal species in the struggle to survive and bringing many species closer to extinction (*Bellisario, B. et al, 2014*). Human society is currently struggling to feed the almost seven billion people on the planet and global warming threatens to make this task more difficult as pasture for livestock and arable land for agriculture slowly become scarcer (*Mendelsohn, R. 2014*).

1.1.2 Energy issues and challenges

The supply and demand of energy, on national scales presents many challenges. These challenges differ from one country to another depending on environmental and economic conditions as well as government policies relating to energy supply, demand and distribution. There are also energy challenges which present themselves regardless of government policies or geographic location and these are; environmental impact, increasing energy efficiency, improving sustainability, and the development of new technologies.

The environmental impact of fossil fuel consumption throughout the world has been the focus of many scientific studies and these studies have documented and quantified these effects. This data has also allowed climate scientists to make future projections on the extent of climate change over the next several decades as well as its effect on global economies (*Taylor et al, 2016*).

The challenge of increasing energy efficiency and improving sustainability presents itself in virtually every facet of modern life, from growing and cooking our food and driving our vehicles to the very clothes we wear, all aspects of modern life require the use of energy in one form or another. The ethos which energy efficiency and sustainability hold at their core demand that we re-evaluate not only how energy is produced at the source but also how much energy we consume as end users. A prime example of this is energy use in the built environment.

1.2 Energy in buildings

Since the 1992 United Nations Framework Convention on Climate Change (UNFCCC), governments around the world in both developed and developing countries have targeted the built environment as one of many focal points in mitigating climate change.

1.2.1 Current impact of buildings

The existence of overwhelming scientific evidence in support of a strong human influence in global climate change has brought about a transformation in the way we think about our built environment. According to (*Ruparathna, R. et al, 2016*) the built environment accounts for approximately 40% of all the final energy consumption and emits 33% of greenhouse gas emissions globally per annum. These factors, when combined pose a significant obstacle to any international policy aiming to mitigate the effects of climate change. To alleviate this issue it would be necessary to increase the thermal performance of existing buildings to as high a standard as possible. The majority of the existing building stock consists of buildings that predate most if not all thermal performance measures currently included in the building regulations and codes. It is for this reason that poorly performing existing building envelopes require special attention.

1.2.2 Current building stock

The existing building stock consists of a wide variety of building types ranging from domestic dwellings to commercial, retail, educational and institutional buildings. It is estimated that 75% of the existing building stock that existed in 2008 will still exist in 2050 (*Ravetz, J. 2008*). This research will concentrate on existing domestic construction, but it should be noted that many of the materials and processes discussed would be applicable to many different building categories.

To be more specific, this research will focus on hard-to-treat dwellings; these buildings are typically of solid wall construction, using materials such as stone, brick and in some but rare cases; earth. According to the Communities and Local Government, English House Condition Survey (2008), currently in the United Kingdom alone it is estimated that there are approximately 6.6 million solid wall dwellings in existence. These hard-to-treat dwellings pose a significant obstacle to instigating climate change policy. These dwelling types do have a role to play; one that will involve a combination of government funding incentives, advanced materials and an understanding of the science behind the transfer of heat, air and moisture in traditional homogenous building materials.

1.2.3 Prospects of new building materials for retrofitting buildings

Retrofit projects present many issues which must be addressed if the project is to be successfully completed. In the case of an insulation retrofit to improve thermal performance, these issues include; material cost per m^2, the type of insulation material such as closed or open cell foams, fiber insulation bat, and material thickness to name a few.

In retrofit projects the type of insulation material is of particular importance, as any material selected would need to be evaluated for its suitability for use with potentially homogenous materials such as stone, brick or even earth. Another concern is the possible effects of moisture on the insulation material; a good example of this is the deterioration in thermal performance of fiber insulation bat when exposed to excessive moisture (*Bjarløv, S. P. et al 2015*).

Based on this information alone, it is clear that retrofit projects demand a detail design process that is the reverse of a new build project, where performance requirements can determine material selection rather than existing materials defining the performance. The development and use of new insulation materials, some of which already exist, would mitigate many of the issues outlined here with retrofit projects.

1.2.4 Need for new materials for hard to treat buildings

The aim is to achieve or surpass these standards as cost effectively as possible with minimal loss of internal room space. Many *off-the-shelf* insulation materials such as Polyisocyanurate (PIR) or Polyurethane (PUR) for example can provide adequate performance levels but the use of these materials to achieve the required retrofit performance, results in a significant loss of internal room space. Retrofit projects on hard-to-treat dwellings in particular have a need for new advanced insulation materials; room space is one of the defining factors when selecting an appropriate insulation material for this type of building.

Over the last 2 decades there has been a substantial amount of scientific research and data gathered on new advanced insulation materials such as Vacuum Insulated Panels or VIP’s and even more recently additional research has been carried out on new aerogel based insulation materials. These new materials demonstrate an ability to achieve the same thermal performance values as PIR and PUR insulation at approximately 10-20% of the thickness. Recent advances in manufacturing technology has also reduced the cost of these advanced insulation materials to the end user, making them a viable alternative to more widely used standard materials. Retrofit projects being carried out on hard-to-treat dwellings now have materials that can maximise thermal performance while minimising loss of room space at costs that are not prohibitive.

1.3 The Present Research Project

1.3.1 Project Aim

Aerogel materials: To study and analyse the performance of a newly developed advanced super-insulating material for retrofitting hard to treat buildings in Scotland, optimise and test its performance and analyse its integration into buildings and benefits, for the primary purpose of proposing a feasible material for retrofitting.

The aerogel material will be tested to determine if it can provide a significant thermal improvement to the performance of an existing building envelope.

1.3.2 Objectives

The objectives of the project can thus be summarised as follows:

1. To study the currently available retrofit and super-insulating materials available on the market to improve hard-to-treat buildings through the literature review.
2. Following the analysis undertaken in (1), to identify the best materials for compatibility and suitability in improving the energy efficiency of hard-to-treat buildings.
3. To test the newly developed material in order to accurately evaluated its performance in laboratory and simulated conditions.
4. To assess industry opinions on the need and value in introducing such new materials on the market.
5. To show the integration of newly developed materials into hard-to-treat buildings and its potential benefits for builders and households.

1.3.3 Research questions

The research questions that this research will aim to answer are;

1. The core aerogel blanket material that is the subject of the research has issues with its on-site workability. Its hydrophobicity and dust generation pose particular issues. Can these issues be mitigated and can this be achieved with minimal impact to the thermal performance of the aerogel?
2. With the introduction of newly developed super-insulation materials such as silica aerogels and polyamide aerogels, can poorly performing Hard-to-Treat existing building envelopes be improved to such an extent that

they will make a valuable contribution toward the mitigation of climate change by satisfying current thermal regulatory requirements?

3. Existing building envelopes are generally constructed of homogenous materials that exhibit bi-directional moisture flow properties. How will the introduction of the new aerogel insulation materials affect these properties?

1.3.4 Outline of the Thesis

Chapter 1 gives the introduction to the thesis, starting from a very broad subject of energy it narrows down to buildings and then to hard-to treat buildings and more particularly the need to address the energy efficiency of such buildings through the development of new materials. It also provides the background, statement and objectives of the present research problem.

Chapter 2 deals with the literature review covering the following topics: (a) Fibrous Insulation Batt, Polyurethane (PUR) & Polyisocyanurate Insulation (PIR), (b) Vacuum Insulation Panels, (c) Phase Change Materials, (d) Dynamic Insulation Materials, (e) Nano Insulation Materials.

Chapter 3 deals with research methodology adopted for this research. The methodology used is introduced followed by the test, measurement and data collection. It also gives laboratory experimental set-up and results with a comparison with previous work. Experimental set-up for the field tests and results of experiments are also provided. Finally an account of uncertainties and propagation of errors through both experimental set-ups is given.

Chapter 4 presents the results and analysis of the tests and demonstrates the potential for the newly developed material to be integrated into buildings and the different considerations to be taken into account when choosing such materials. Benefits in installing such materials and possible installations are also provided.

Chapter 5 draws up important conclusions from the simulated results stemming from the data presented in chapter four.

Chapter 6 discussion of the interview results and analysis.

Chapter 7 discusses conclusions based on the research.

1.4 Concluding remarks

This chapter provides a detailed introduction to energy, its various resources, associated issues and challenges and its current and future status. Significance of buildings energy demand was established and various forms of buildings discussed. Hard-to-treat buildings were addressed in detail as this forms the basis of the present project. The need for new materials to be developed to improve the energy efficiency of hard-to-treat buildings was also emphasised. This was followed by stating the research problem, its aims and objectives and finally the structure of the thesis.

CHAPTER 2 LITERATURE REVIEW

In the context of the present research project, investigating retrofitting of hard-to-treat buildings has three core aspects. The first is studying the prospects and diversity of hard-to-treat buildings. The second aspect deals with the assessment of current materials available for retrofitting and more importantly new advanced super-insulating materials. The third involves the pros and cons of aerogel as a retrofitting material and the many considerations that need to be taken into account. This chapter is accordingly sub-divided into three sections. Section 2.1 reviews the different types of Hard-to-treat buildings as well as the considerations to be taken with each. Section 2.2 provides a comprehensive yet summarised coverage of the different types of insulation materials available. Section 2.3 discusses the properties of aerogel insulation and its applications to buildings.

2.1 Hard-to-treat buildings

The term “Hard-to-treat” in the context of the built environment is an umbrella term used to describe a wide variety of buildings in which difficulties arise when attempting to improve their energy performance.

2.1.1 Description and Types

Any building constructed of homogeneous materials such as stone, brick or earth for example can be described as hard-to-treat. Homogeneous building materials present issues where improvements to the thermal envelope are concerned. There is evidence which demonstrates that unsuitable insulation material and unsatisfactory detailing result in issues with mould growth or a degradation of the envelope material over time (Airaksinen et al, 2004). This is due to an inability of the material to dry out and expel excessive moisture. There are various types of hard-to-treat buildings, ranging from historic buildings, domestic dwelling houses, multi-story apartments, to industrial and commercial buildings (*BRE, 2008*).

2.1.2 Limitations to energy efficiency retrofitting options

Poor energy performance can be mitigated in a number of ways, such as introducing a more efficient boiler for hot water and space heating, attic and or floor insulation are another option. The reduction of air infiltration can also help energy performance; these options are less intrusive both practically and visually for the occupier. The main issue in improving the energy performance of hard-to-treat buildings presents itself when an external wall component of the buildings envelope requires a thermal upgrade.

In the case of historic buildings the limitations to energy efficiency retrofitting options are more prominent than in the majority of other hard-to-treat buildings types. Any internal or external retrofit that would constitute an aesthetic alteration to the building's interior walls or exterior façade will face strict planning restrictions *(Historic England 2012)*. A thermal upgrade to an existing wall component is a worthy example. Visible elements such as pilasters, corbels, cornices, architraves, dado rails and many other features will be obscured or completely hidden by an internal or externally applied insulation material.

These limitations are also applicable to any building type considered to be of architectural significance which includes any of the building types mentioned earlier. In addition to this there are also limitations due to certain existing materials such as the presence of asbestos which will require costly removal or no interference at all.

One limitation which overrides all others is the cost / benefit of the retrofit itself; if the cost of the energy efficiency upgrade does not result in an adequate cost reduction for energy consumption, then there will not be adequate justification for the retrofit. This consideration is of paramount importance when considering a thermal upgrade to the building envelope of a hard-to-treat dwelling.

2.1.3 Performance considerations for retrofitting

There are many considerations to be taken into account when planning a retrofit to an existing building. The process becomes even more complex when we consider that each retrofit project is unique to that particular building. Before any work is carried out on a retrofit project an assessment of the buildings current annual energy costs will be required; this will allow for an informed decision as to the most cost effect upgrade for that particular building *(Fletcher et al 2016).* This analysis will identify the current level of energy performance of the building prior to the retrofit and thus will allow for a calculated comparison of projected performance levels using a variety of different insulation materials, each with different thermal conductivities.

This process is an important step as not all insulation materials will be appropriate and cost effective. Once it can be shown that the cost of the retrofit can be off set against the payback period within the life span of the insulation material then the retrofit can be justified. Another consideration to be accounted for is the expected level of performance after the envelope has been upgraded; the current building regulations state the required level of performance that a wall component in an existing building envelope should achieve after retrofit.

Consideration A - Energy performance

According to the current building regulations in Scotland for example, the required U-Value for any refurbishment work to an existing building envelope is 0.70 Wm^2K for a wall *(Technical Hand Book 6: Energy, 2015)*. It is not realistic to expect existing building envelopes to achieve the same performance standards as those in new buildings. In acknowledgement of this, the required standards have been relaxed to a significant degree.

Consideration B - Moisture performance

Moisture transfer through an existing building envelope can have a critical role in the thermal performance of any building component. The inclusion of moisture transfer in the research will also allow its effects on the performance of the aerogel based insulation material to be studied. Data can be collected and analysed to determine the overall impact of moisture movement on the internally insulated existing wall types used in the thermal performance analysis.

Consideration C - Practicality / Design performance

Geometry is a component part of the DNA of architecture and scientific research has shown that the geometry of a building plays an important part in building energy consumption also referred to as design performance. Other aspects of design performance relate to the effects a retrofit design will have on the performance of the building envelope (*Hemsath, T. L. et al, 2015*). The practicalities and intended design performance of any retrofit involving the thermal upgrade of hard-to-treat dwellings will all have a series of common issues that must be considered at the design stage. These issues may be mitigated or exacerbated by the building geometry, choice of insulation materials and type of homogeneous wall material present in the existing building envelope. These common issues are discussed in the next section.

2.2 Types of insulation materials currently available

There are many types of insulation materials widely available to the construction industry; the list below identifies some of the most common types;

a. Mineral Wool
b. Cellulose
c. EPS (*Expanded Polystyrene*) & XPS (*Extruded Polystyrene*)
d. PUR *(Polyurethane)*

2.2.1 Typical materials

Currently in both the UK and the US similar materials are used for thermal upgrades. The materials mentioned earlier in section 2.2 are considered typical for a variety of different project types such as domestic and commercial construction projects. (*Biswas, K. et al 2016*)

Material 1 - Glass Fiber / Mineral Wool Insulation

Characteristics:

Mineral wool can be described as a lightweight fibrous insulation batt material which can be easily handled, cut and placed in position. The material can be supplied in as flexible or in a denser more rigid form. The material is manufactured by a process which involves the spinning of molten natural and / or synthetic minerals and collecting the resulting fibres, these fibres are then processed into one of the two types described above.

Advantages and Disadvantages:

Mineral wool has an average thermal conductivity of 0.035 W/mK, its thermal conductivity can vary depending on the type of mineral used to create the final product. In addition to this, it can be easily applied to a wide variety of wall types, such as solid, timber frame or double leafed walls.

Other advantages include ease of transportation and fire resistance. Mineral wool has an *R value* of R4.6 per inch which places it in the same performance level as PIR, PUR and XPS insulation.

The material also has various issues which must also be considered, for example; if the fibrous fleece material becomes damp or waterlogged, this can increase thermal conductivity within the envelope component thus reducing the overall thermal performance of mineral wool when compared to other insulation materials. (*Hauser, G. et al 2013*)

Applicability to buildings & Retrofit Projects:

Mineral wool has a high level of applicability to retrofit projects, this is based on current wide spread industry use, amounting to 60% of the market and research into its performance and properties. As discussed earlier, mineral wool has been shown to have a reduced level of thermal performance when liquid moisture develops within the insulation material. According to *Jiřičková, M. et al (2006*) manufacturers have overcome these issues by the introduction of hydrophobization; this process allows the material to repel any significant moisture build up thus maintaining its thermal performance.

Material 2 – Cellulose Fiber Insulation (CFI)

Characteristics:

Cellulose is a fibrous recycled paper based insulation material. The material can be produced in the form of rigid panels where the material is moulded using a polyester binder or in a sprayable form. The sprayable form consists of the cellulose material in the form of “mulch” which is mixed with either water or an adhesive or in some cases both, and sprayed into an attic space, onto a wall or floor.

Advantages and Disadvantages:

Some of the advantages of using Cellulose insulation are its ease of application. The spray application process greatly reduces the time taken for application thus keeping labour costs low. In addition to this, cellulose is manufactured from recycled office paper at approx. 67% content or recycled newspaper at approx.

48% content. The high mass ratio of recycled raw materials used in cellulose production means that its embodied energy is low compared to other insulation materials. For example; cellulose has an embodied energy of 0.094 – 3.3 MJ/kg whereas mineral wool is 16.6 MJ/kg.

Cellulose has been shown to moderate variations in relative humidity by its vapor permeability properties; this buffering effect has been cited by manufacturers of the materials as advantageous in controlling mould growth and allergies.

Cellulose has a higher thermal conductivity then many other insulation materials being 0.04 W/mK, this can be a disadvantage but it should be noted that depending on the type of project, the relatively minor decrease in performance can be off-set by its embodied energy as well as its moisture buffering properties. (*Hurtado, P. L. et al 2015*)

Applicability to buildings & Retrofit Projects:

Cellulose insulation is ideally spray applied for both speed and ease of application. This process, in terms of its applicability to building and retrofit projects has the potential to be problematic, specifically in retrofit projects on hard-to treat walls. Hard-to treat walls by their nature are solid masonry walls constructed of stone, brick, concrete block or mass concrete. Any interior cellulose application to these wall types would require additional interior dry lining involving the use of timber studs and plasterboard, the thermal performance of the material will determine the depth of the dry lining.

Given that, the thermal conductivity of cellulose is 0.04 W/mK a significant loss of interior room space will occur. Cellulose is therefore perfectly applicable to projects that involve new construction or retrofit projects where dry lining has been included and accounted for in the design, but for the approx. 6.6 million hard-to-treat dwellings in the UK, cellulose may not be an appropriate choice of insulation material due to the thickness needed to achieve regulation standards.

Material 3 – Polyurethane PUR

Characteristics:

Polyurethanes were developed in the 1940's by Prof. Otto Bayer as a replacement for rubber. In the years following its successful development, the process of polyurethane manufacture had evolved to a stage where this material was available in a wide variety of forms and suitable for a variety of end use applications. Today polyurethane is used in the automotive industry, clothing manufacture, machine components, product manufacture and signage and as insulation in the building industry.

Polyurethanes are produced by a resulting chemical reaction between a Polyol and Diisocyanate. During this process a wide range of additives can be introduced to the process resulting in the many variations of polyurethanes available today.

Advantages and Disadvantages:

Polyurethane has many advantages resulting from its variety of forms and uses. This property alone is highly advantageous in the building industry as any material with insulation properties that can be manufactured in rigid, flexible or spray form has applications to almost every facet of the building industry. This level of versatility allows polyurethane to be used as wall, floor and attic insulation in both new and retrofit construction projects.

In terms of its disadvantages, there are the issues of its environmental impact during the manufacturing process, which involves the use of organic chemical compounds which could pose a threat to nearby ecology. This also raises the issue of its sustainability and embodied energy. As mentioned earlier, polyurethane is the result of a chemical reaction between Polyols and Diisocyanate, themselves requiring a production process.

The embodied energy of polyurethane according to the *University Of Bath, Inventory of Carbon & Energy* (2011), is 72.10 MJ/kg in its raw state and after further processing this figure increases to 101.5 MJ/kg for rigid polyurethane insulation.

Applicability to buildings and Retrofit Projects:

Polyurethane foam has a thermal conductivity of 0.02 – 0.029 W/mK according to *Cuce et al. (2014*), this is an adequate level of thermal performance for construction purposes and is comparable to other materials such as Polyisocyanurate and Cellulose insulations. Polyurethane insulation has the advantage of flexibility that Polyisocyanurate does not which is advantageous particularly in retrofit projects where insulation may be required in complex spaces. In addition to this there is also the wide availability of the material in a variety of thicknesses for a diverse range of projects where traditional materials form the main component to be insulated such as stone or brick walls, stone or concrete floors and attic spaces.

2.2.2 Hybrid and thermal mitigation systems

Types of “hybrid” and thermal mitigation systems available such as Dynamic Insulation Materials (DIM’s), Phase Change Materials (PCM’s) and Vacuum Insulation Panels (VIP’s) are discussed below.

Dynamic Insulation Materials (DIM’s)

Characteristics:

A DIM or Dynamic insulation material allows for the controlled movement of moisture within the building envelope. This property of DIM’s is important as moisture movement is a key agent in the level of thermal performance of any insulation material. DIM’s are usually composites comprising the insulation material and an interior surface component. Depending on the type of base structure, DIM’s can be designed to either transport or restrict moisture flow. (*Bomberg 2010)*

Advantages and Disadvantages:

DIM’s have a wide range of applicability to both new and existing structures such as masonry cavity walls, timber construction and traditional solid stone or brick walls. One of the main advantages of this type of insulation system is that it has been shown to mitigate issues associated to mould growth with the building envelope and also with indoor air quality (*Bomberg 2010*).

Applicability to buildings and Retrofit Projects

The applicability of dynamic insulation to retrofit projects may be more appropriate in projects involving traditional solid walls. The main reason for this is that traditional solid walls tend to be constructed from homogeneous materials such as solid stone, solid brick or earth. These materials traditionally do not have vapour barriers and therefore exhibit bi-directional moisture movement. Care needs to be taken when applying insulation to these types of wall structures; dynamic insulation can attenuate occupancy induced vapour pressure from inside to outside, while also allowing the homogeneous materials to breathe naturally. This is an important property when dealing with traditional structures.

Phase Change Materials (PCM's)

Characteristics:

PCM's or Phase Change Materials are materials that change their form when they experience a change in temperature. This property is not as exotic as it may first seem and materials of this nature can be found to be quite common. For example; water is a phase change material, at ambient room temperature it is a liquid, when its temperature is cold enough it will become solid in the form of ice and when hot enough it will change phase to a gaseous vapour known as steam.

PCM's are a latent heat thermal storage system, the materials absorb heat energy and as a result they change phase. This condition will remain constant as long as the temperature remains within the range necessary to induce the phase change. If however the ambient temperature drops the heat energy absorbed by the material will be released hence the term "latent heat thermal storage system" (*Kalnaes et al 2015*).This is a physical property which has recently been exploited for use in the built environment as a means to conserve and regulate energy use in buildings.

Advantages and Disadvantages:

Phase change materials have the ability to both store thermal energy and also release it. This property is not only controllable but materials are available which exhibit this characteristic at room temperature.

According to *Kalnaes et al (2015*) these materials are utilised in three main forms, 1-Organic materials, 2-Inorganic materials and 3-Eutectic materials. Currently the most common and viable material used in PCM development is paraffin. This material is organic and exhibits phase change capability at room temperatures. Paraffin's are also easy to produce and inexpensive.

There are some disadvantages to using Paraffin's, namely health issues. According to the IARC, International Agency for Research on Cancer, paraffin's are considered to be a "possible carcinogen".

Applicability to buildings & Retrofit Projects:

According to *Baetens et al (2010*), the temperature stabilisation that results from the use of PCM's has practical applications within the built environment. A reduction in energy consumption due to reduced heating and cooling demand reduces energy costs and ultimately benefits the consumer as well as the environment.

This type of latent heat exchange system is more suitable to newer well insulated building envelopes than it would be to traditional solid wall building envelopes constructed of homogeneous materials. The reason for this is because solid walls already act as a latent heat thermal storage system due to their thermal mass where as more modern well insulated walls tend to be much less thermally massive and more reactive to temperature changes.

It must be pointed out that the use of PCM's on solid walls would be justified if the solid walls have been insulated. Insulation immediately negates the thermal mass of the wall and thus the PCM's ability to induce temperature stabilisation would become a justified additional component.

2.2.3 Vacuum Insulation Panels

Characteristics:

Vacuum insulated panels are fully encapsulated composite vacuum panels which contain high performance insulation as its core material and also a laminate material which functions as the encapsulation. This type of insulation material is used where thermal performance needs to be maximized and loss of space reduced to an absolute minimum, such as refrigerators, freezers and cold shipping containers. A large portion of the high performance level is due to the presence of the vacuum, this will be seen in the following section as both an advantage and disadvantage. VIP's were originally developed in the early 1980's as a high performance alternative to existing industry standard insulations such as Styrofoam for example which require the presence of Chlorofluorocarbons CFC's in their production process. *(Johansen et al 2014)*

Advantages and Disadvantages:

Vacuum insulated panels offer two obvious advantages over standard insulation materials; a very low thermal conductivity and minimal material thickness. According to *Johansen et al (2014*), a typical VIP has a thermal conductivity of

0.007 W/mK at a thickness of 20mm. The use of VIP’s in refrigerators, freezers and cold shipping containers is an efficient and cost effective means of allowing a maximum amount of goods such as perishable foods and other items to be transported over long distances due to the small loss of space required by the use of VIP’s.

There are however several disadvantages; due to the nature of how VIP’s function, they must be manufactured to a predefined set of shapes and thicknesses. This means that this form of insulation is not conducive to on-site alterations to its shape such as the cut & fit process that takes place regularly on construction sites with most standard insulation materials. If the encapsulation of the panel is compromised in any way and the vacuum component is lost, the thermal performance is greatly reduced.

Applicability to buildings and Retrofit Projects:

VIP’s have a high degree of applicability to construction projects, both new and retrofit. The applicability of VIP’s to such projects comes with difficulties as outlined by *Johansen et al (2014);* each construction project would essentially require a set of panels designed specifically for that particular project. Elements of the structure in question would also need to be carefully considered such as the type of building envelope, the condition of the structure and its suitability to the insulation measures in question. Potential issues such as settlement cracks, internal and external angles that are less than or greater than 90 degrees and quality of the surface to which the new insulation measure is to be applied to. For example; is the internal or external wall surface flat? Many traditional buildings do not have smooth flat walls as they tend to warp and “buckle” over time. In many cases, these issues could render the use of VIP’s as unsuitable, hence the need for an accurate assessment of suitability prior to commencing project work.

Once the appropriateness has been determined, care must also be taken when applying finishes. The mounting of fixtures to the surface of a wall which has been retrofitted with VIP’s can also have a detrimental effect on the performance of the insulation material in the event of the encapsulation being punctured as mentioned earlier.

From an applicability point of view it can be seen that VIP's have the potential to dramatically improve the overall performance of a new or existing building, but considerable planning is required and later additional alterations to the structure or building envelope need to be very carefully planned.

One very interesting sidebar to the main focus of the literature review was a description of the effects of "*Phonon Tunnelling*" in thermal systems that include a vacuum. This process describes how heat transfer can take place in a thermal vacuum system due to acoustical waves aiding heat transfer between individual atoms also known as atom lattice vibrations. The overall effect is a slight increase in the observed thermal conductivity when compared to the calculated one; this process would therefore have an extremely small but measurable effect on such systems as vacuum insulated panels.

2.2.4 Advanced super-insulating materials

Types of super insulation materials such as Silica Aerogels and Polyamide Aerogels will provide high performance ultra-thin alternatives to the materials currently available. Silica aerogels have already made the transition from the laboratory to the construction site but polyamide aerogels still need to overcome the issues raised by industrial scale production processes that were also faced by manufacturers of silica aerogel just a few decades ago.

Even though; silica aerogels are still considered a niche market product within the construction industry. Specifiers such as architects and engineers will need to become more accepting of new materials and embrace more creative solutions. Presently; super insulators in general such as aerogels are not currently considered to be conventional insulation products within the construction industry.

Silica Aerogels

Characteristics:

Silica Aerogels have been available for several decades for space exploration and about fifteen years in the petrochemical industry. Until relatively recently, silica aerogels have not been able to gain a foot hold in the construction industry mainly due to issues relating to manufacturing costs. New developments in manufacturing processes have reduced costs over the last 10 years and presently; silica aerogel products are becoming more common in construction projects, although at a small scale (*Smith, D. M. et al, 1998*).

Advantages and Disadvantages:

Some of the issues silica aerogels faced in the earlier stages of its commercialization have been outlined by *Smith, D. M. et al, (1998*). Issues such as the insulation shape and form, flammability, mechanical strength, durability and material lifecycle needed to be addressed and understood for the material to become fully commercially viable.

Some current silica aerogel insulation products still exhibit problematic characteristics. For example; the silica aerogel “blanket” material manufactured by Aspen Aerogels Inc. has a very high degree of applicability to the construction industry, but there are issues with this material. When this product is cut it tends to produce significant quantities of aerogel dust, this carries with it the possibility for irritation of the respiratory system. This material also has a high level of hydrophobicity which is artificially added during manufacturing to make the product more resistant to moisture. The problem with this is that if the hydrophobic aerogel particles come into contact with skin it can cause the skin to dry out and induce skin irritation and excessive itching, this is also problematic for the eyes. When these factors are all considered collectively they require the end user to wear full personal protective equipment such as overalls, protective goggles and a dust mask, according to Aspen Aerogel Inc. Material Safety Data Sheet for their product, Spaceloft ©.

The overwhelming benefit of using silica aerogel is its low thermal conductivity.

Applicability to buildings and Retrofit Projects:

Silica aerogel in composite form, such as the insulation blanket manufactured by Aspen Aerogels Inc. offer many advantageous characteristics. For example; a thermal conductivity of 0.015 W/mK, minimal loss of internal floor space and resistance to moisture due to its hydrophobicity. According to *Jelle B. P. (2011)* Aerogels are the most promising with the highest potential of all the commercially available superinsulators, with some aerogel materials offering thermal conductivities as low as 0.004W/mK.

In terms of its applicability to buildings and specifically retrofit projects; aerogels have precisely the correct material characteristics for these types of projects. According to *Hostler, S. R. et al (2009)*, in a study which was financed by Aeroclay^{tm}, it was found that aerogel particles could be incorporated into a clay base material to form a composite successfully. Other research has demonstrated aerogel being used for internal and external renders as well as glazing demonstrated by *Schultz, J. M. (2005)*. Also according to *Gao, T. et al (2014)* approx. 50% of a buildings energy loss can be attributed to its fenestration, and this paper explores options for using commercially available aerogel materials in an attempt to abate energy loss as much as possible.

Polyimide Aerogels

Characteristics:

According to *He, S. et al (2015),* Polyimide aerogels have outstanding mechanical properties and temperature stability. Over the last several years Dr Anne Meador from the NASA Glenn Research Centre carried out and recently completed ground breaking developments on Polyimide Aerogel in both flexible and solid forms. This is an important step for aerogel based materials as these developments with polyimide aerogels are the first to produce robust high performance thermally insulating plastics.

Advantages and Disadvantages:

According to *Meador, M. et al (2011)* flexible polyimide aerogel materials have been developed by NASA as inflatable aerodynamic breaking systems such as the LDSD – Low Density Supersonic Decelerator. This is an extreme example of the temperatures, and conditions this material can be exposed to, but the important point here is that the polyimide component of the materials provides the mechanical properties. With an ability to perform under such extreme conditions it is clear that there are a wide variety of possible applications for such a material.

The disadvantage of this material at present is that it is still a relatively new material and currently finds use in applications with exceptionally high budgetary costs, such as space exploration. It is reasonable to conclude that this material will one day be used as a high performance flexible insulation material for everyday commercial use.

Applicability to buildings and Retrofit Projects:

Polyimide aerogels have a vast array of applicability to the construction industry but this material is not currently available due to its very recent development and current cost.

Hypothetically; if this material were available to the construction industry then the potential applications would range from high spec volumetric off-site construction where a high level of energy performance is critical and practical to achieve, to retrofit projects where insulation solutions are sought for difficult detailing issues and energy performance improvements.

2.3 Silica Aerogel

2.3.1 Properties of silica aerogel

Silica aerogel was invented around 1930 by Dr Samuel Stephens Kistler. The aerogel is formed by a process known as super critical drying, in which a sol gel solution consisting of tetramethoxysilane or tetraethoxysilane has its liquid portion evaporated, leaving behind the aerogels solid skeletal nanostructure. This is a very simple explanation of what is actually a three step process. To gain a better understanding of the aerogel structure it is necessary to consider it at a microscopic level. After the process of super critical drying has been completed the aerogel, at the microscopic level, consists of a skeletal structure composed of nano spheres. These nano spheres are generally in the order of about 20 nanometres in diameter but can be larger than 100 nm. They form chains of nano spheres where each individual nano sphere is linked to another as well as chain to chain (*International Sol-Gel Society, 2011)*

The silica aerogels nano sphere structure allows a low thermal conductivity of 0.010 to 0.016 W/mK to be achieved**.** A key factor influencing the low thermal conductivity is the area that forms the bond between the individual nano spheres. Given that the spheres are roughly 20 nm in diameter, the area of the bond between the spheres is significantly smaller; anywhere from 1 to about 5 nm in diameter. Any thermal energy conducted from nano sphere to nano sphere must pass through the area of the bond. Therefore it is the actual area of the bond that determines the rate of thermal conductivity (*Sandberg et al, 2013)*

Aerogel in its pure form has some disadvantages which render it virtually unusable in a real-world construction application, for example; the aerogel skeletal structure is extremely brittle and can easily be reduced to a fine powder with relatively little effort**.** Therefore the application of aerogel as an insulator in a building envelope would require a significantly more robust approach. Identifying an appropriate form of aerogel product; one that would have the robustness required for a variety of building applications is therefore required.

2.3.2 Aerogel based materials and systems

Ibrahim et al (2014) tested a newly patented aerogel based external render on a series of existing wall samples. The aim of this research was to gather data on the effects this insulation render would have on the hygrothermal performance of a variety of existing wall types.

This work also used WUFI Pro 5.1 to carry out a simulated analysis of the data for comparison purposes and also identifies the risks posed by the use of interior insulation products. Issues such as excessive moisture build up within the fabric of the wall structure and the related issues of mould growth and the possible health problems associated with mould growth were discussed. The work concludes that externally applied aerogel based renders can significantly improve the thermal performance of an insulated or uninsulated existing wall while mitigating the issues of mould growth and its effects on occupants.

Another earlier study carried out by *Stahl et al (2011)*, also examines the thermo-hygric properties of aerogel based renders on existing walls. One particularly interesting point to note in this paper is that it identified a difference in the thermal performance of the aerogel based render between samples that were machine applied and those that were applied by hand. This issue has also been noticed in conventional insulation renders. The cause of the drop in performance has been explained by the higher water intrusion of the render due to the use of the plastering machine. In brief, the research concluded that further research was required to determine suitable ratios of admixtures to the render compound in order to maximise its thermo-hygric performance.

Hostler et al (2009) carried out an investigation of the thermal properties of clay based aerogels. This research identifies the advantages of introducing polymers such as Polyvinyl Alcohol into the aerogel clay to increase its strength properties. This study demonstrated that not only did the introduction of the

Polyvinyl Alcohol add to the strength of the aerogel based clay but it also assisted in reducing the thermal conductivity of the material. The researchers speculated that the cause of this reduction may be due to a more complex interaction between the admixture and the clay than the model assumed.
Other research involved a compacted granular silica aerogel filled truss-core sandwich panel. An investigation into this type of construction element was conducted by *Chen et al (2014)*, and focused on the thermal and structural properties of the system. It concluded that the truss core panel, when filled with aerogel granules, maintained a high level of thermal performance, and the research showed that aerogels have a wide range of applications in the construction industry as stand- alone insulation but also as a component part of a building element or a construction system. The literature review has shown that there is a wide array of possible uses for aerogel, in both internal and external construction applications.

2.3.3 Aerogels in building applications

Recent and current state-of-the-art research being carried out using aerogels in building applications is provided below.
The impact of aerogel insulation on the thermal performance of existing building envelopes can be characterized under the following headings:

- Thermal Performance
- Acoustic Properties
- Fire Behaviour

It should be noted that these characteristics are dependent on the way the aerogel has been used; for example if the aerogel forms part of an internal or external render or if it is used in a blanket or panelised form. For the purposes of this section, the blanket insulation will be used, as currently this is the most practical form of aerogel composite available to the construction market.

Thermal performance: this has been discussed in previous sections but in a building application, the thermal performance of aerogel can greatly affect the performance of the entire building component, such as a floor, wall or roof component. Evidence for this is supported by extensive research carried out by Historic Scotland. According to *Baker et al (2011)*, it was found that typical U values for traditional solid walls measuring 600mm (2') thick range from 0.9 to 1.1 W/m^{2}K, with an internal finish of plasterboard and plaster on lath respectively. Traditional building envelopes such as those mentioned in *Baker et al (2011)* are an excellent example of a situation where the use of an appropriate aerogel composite insulation material would make a significant contribution to the thermal performance of the wall. This type of situation will be discussed in greater detail later where simulated calculations will identify how the introduction of aerogel will affect the overall performance of traditional building envelopes among other forms of envelope construction using simulation software.

Acoustic Properties: According to *Forest et al (2001)*, Granular aerogels are exceptional reflectors of audible sound and monolithic silica aerogels have a lower speed of sound than air, measuring approx. 40m/s. Further sound attenuation has been observed in multi-layered systems.

Fire Behaviour: According to Aspen Aerogels *Spaceloft Safety Data Sheet*, the commercially available aerogel blanket is considered to be “Difficult to ignite” with a classification of C-s1,d0.

2.4 Life Cycle Assessment & Embodied Energy / Carbon

The existing built environment offers a unique stand point from which to tackle the issues of climate change. As mentioned earlier in the literature review, many innovative materials and systems exist that would improve the thermal performance of an existing building envelope, but another important question to ask is the environmental cost of these materials. To understand the environmental cost of any material it is necessary to evaluate the material from several aspects and answer the following questions; 1. How much energy is used in the mining, manufacture and / or processing of the material 2. How much energy is used in the transportation of the material 3. What is the life expectancy of the material once it is in place? (*Historic Scotland Technical Paper 13 2011).* The third point is an important factor as it is possible to offset a high initial energy cost for the extraction and / or production of an extremely durable material with a long life expectancy.

One very good example of this is stone. Stone is a material that has a high initial energy cost from source to site, but when considering that stone is a natural material that can last for hundreds if not thousands of years with relatively little to no maintenance, it becomes apparent that the initial high energy cost was in fact justified. The reciprocal of this is concrete. This material is essentially a composite material consisting of sand, cement, aggregate, water and various types of admixtures depending on its end use. Concrete like stone can last for hundreds if not thousands of years hence the existence today of the colosseum and the roman forum, all of which were constructed using an early form of concrete. The Achilles heel of concrete is the fact that unlike stone used in construction, it is a non-homogenous composite material, requiring extensive and energy demanding heavy manufacturing processes to produce the final product. According to the (*Circular Ecology; Inventory of Carbon Database),* the following types of stone have their respective embodied energies listed below, measured in MJ/kg.

Material	Embodied Energy MJ/kg	Embodied Carbon CO_2/kg
General	**1.26**	**0.073**
Granite	**11.00**	**0.64**
Limestone	**1.50**	**0.087**
Marble	**2.00**	**0.116**
Marble tile	**3.33**	**0.192**
Sandstone	**1.00**	**0.058**
Shale	**0.03**	**0.002**
Slate	**0.1 to 1.0**	**0.006 to 0.058**

Table (1) Embodied Energy / Carbon of stone. *Circular Ecology; Inventory of Carbon Database*

The vast majority of building envelope components can be assessed with regard to their respective embodied energies, but as this research will mainly consider existing building envelopes; the embodied energy of each existing envelope component is less relevant. This research will therefore focus on a comparison of the embodied energies of any new component added to the existing envelope and thus will consider a variety of insulation materials such as EPS, Mineral Wool, PIR, PUR, VIP’s and Silica Aerogel.

There are many other forms of insulation materials and systems that could be considered such as NIM's, DIM's and PCM's, all of which offer a higher level of performance to most conventional insulation materials. This research will concentrate on a comparison between Silica aerogel and more conventional insulation materials, as these materials will form the aerogels main competitors currently available within today's construction industry.

As mentioned earlier in this report, obtaining valuable data and relevant research on Silica aerogel and its uses in the construction industry has proven quite difficult on all fronts as sources are limited. The only embodied energy data available for Silica aerogels comes from *Aspen Aerogels LLC* and refers specifically to opaque aerogel blankets for which a figure of **53.9 MJ/kg** with a carbon burden of **4.3 kgCO$_2$/kg** is provided. According to the *(Circular Ecology; Inventory of Carbon and Energy),* this figure is considered "high" when compared to conventional insulation materials.

Table 2 outlines the embodied energies for Aerogel and its current competitor materials.

Material	**EE MJ/kg**	**EC kgCO$_2$/kg**
Mineral Wool	16.6	1.20
EPS	88.6	2.55
PUR	101.5	3.48
Silica Aerogel	**53.9**	**4.30** (*Aspen Aerogels*)

Table (2) Inventory of Carbon and Energy. *Circular Ecology; Inventory of Carbon Database*

Based on the information in Table (2) Silica aerogel can be seen to be reasonably high as mentioned earlier, but the aerogel blankets durability and thickness could be a highly influential factor when designing for retrofit projects. It is important to note that aerogel does have significant benefits over the use of VIP's where durability is concerned, and its advantages over mineral wool stem from its higher *R value* per inch thus saving internal room space.

According to *Menzies (2013)*, in many cases the effectiveness of low carbon retrofits in traditional building envelopes only tend to make carbon evaluations based on the production of any materials used in a retrofit project, transportation of that material and any carbon saving after the retrofit project. This type of analysis however ignores one additional factor from consideration: the total energy expenditure during the retrofit process. This is taken as the energy cost of the removal and disposal of any part not considered to be sufficiently energy efficient in the retrofit of a building component.

Life cycle analysis (LCA) includes the entire life cycle of a product, process or system: encompassing the extraction and processing of raw materials; manufacturing, transportation and distribution; and use, reuse, maintenance, recycling and final disposal (*Consoli et al 1993)*.

To streamline an LCA for the use of a super insulator such as aerogel in a retrofit project involving a traditional building envelope, the factors mentioned above by *Consoli et al (1993)* make it clear that these types of calculations are greatly dependant on many variables. As a result, the total carbon expenditure for a given project will be unique for that project. As long as the total carbon expenditure for a retrofit project is less than the total carbon saved as a result of the retrofit over the expected lifecycle of the material, the entire process will have been justified. If this can be done on a global scale then the contribution our existing built environment can make towards mitigating climate change becomes apparent. If not, then nothing has been achieved from an environmental aspect and the built environment will continue to contribute to climate change.

2.5 Concluding remarks

A review of the three core aspects of the research was presented herein. First; relevant commercially available insulation materials were identified described and characterized using data from a variety of research sources. This data outlined the processes, by which the materials are manufactured as well as the various forms in which they are available to the end user. It was necessary to obtain this information as it ties directly into the following core aspects of each material.

Second; the advantages and disadvantages of each material was researched and discussed. This form of appraisal was conducted with a view to identifying the various issues which need to be considered when selecting a material for a particular type of project. Considerations such as suitability of the insulation material to the type of building component to be upgraded and the suitability of the insulation material to the existing materials are important considerations. The research has shown that the form of the insulation such as open or closed cell Polyurethane or Polyisocyanurate, Cellulose, Fiberglass quilt or Aerogel all present a variety of pros and cons that will determine their applicability to retro-fit building projects.

Third; after the various materials had been described and characterized, and had also been assessed in relation to the respective pros and cons, it was then necessary to evaluate the level of applicability of each material to building and specifically retro-fit projects. These types of projects present unique challenges as they require solutions to existing problems to be found as opposed to new build projects where issues can be addressed during the design phase of the project. The applicability of an insulation upgrade will depend on many factors such as the level of thermal improvement, fire behaviour and acoustical properties. In addition to these factors other considerations would include, required thickness of the insulation and methods of mechanical fixing to the existing substrate.

To sum up; the literature review has shown that of the current body of research available, although extensive and in-depth, only a small portion of the research specifically refers to how aerogel based super insulation blankets will affect the existing building envelopes they may be applied to. The literature review has shown that the majority of research and test data referring to thermal performance on existing solid walls has been carried out on both insulated and uninsulated solid walls using conventional materials such as Polyisocyanurate (PIR) and Polyurethane (PUR) among others. There are some exceptions; research funded by Historic Scotland and carried out by the Scottish Energy Centre at Edinburgh Napier University, described in *Historic Scotland Technical Paper 19 (2013)*. This research will aim to capitalize on this previous research and expand it to include brick, stone and hybrid walls.

Insulation Material	**Physical Properties**			
	Thermal Conductivity W/mk (l)	Specific Heat Capacity J/kgK (*Cp*)	Bulk Density kg/m$_3$ (r)	Vapor Resistance Factor
Aerogel	0.015	1000	146	4.7
PUR Insulation	0.025	1500	40	50
PIR Insulation	0.024	1470	26.5	51.3
Mineral Wool	0.04	850	60	1.3
Batt Insulation	0.043	840	88	1.21
Cellulose	0.04	2500	70	1.5

Material data taken from WUFI 5.2 material database.

Table (3) Comparison of materials & their physical properties.

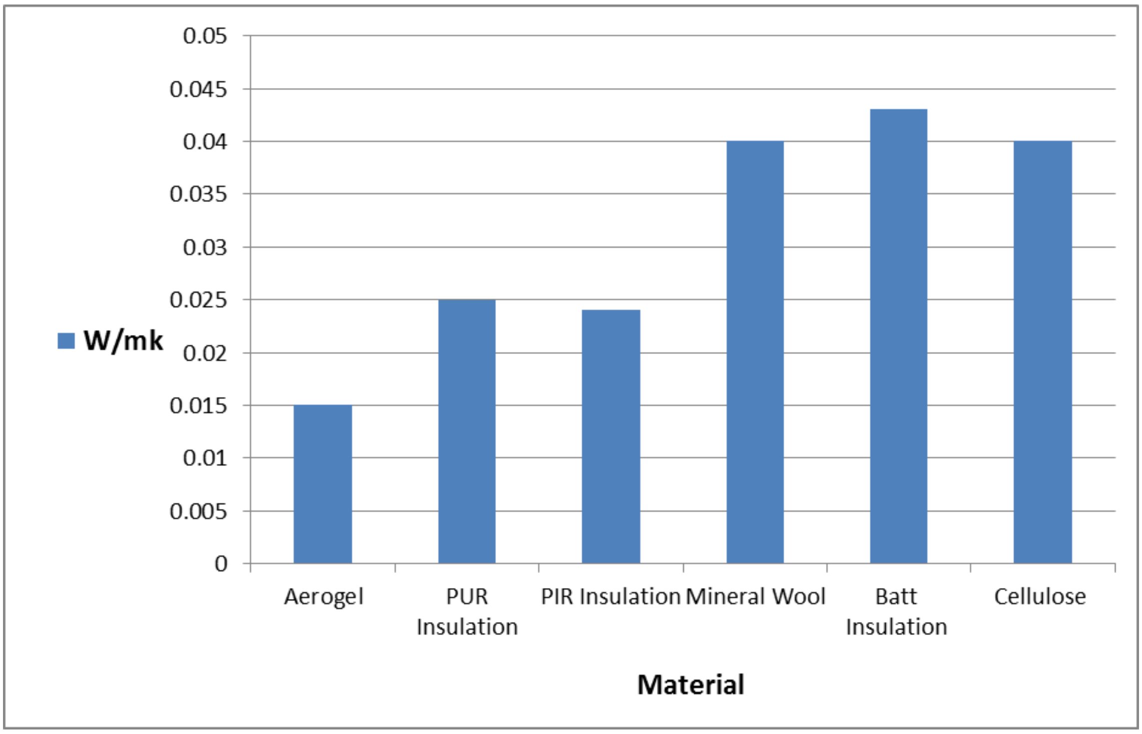


Fig (1). Histogram showing thermal conductivity for each material.

Room Area Reduction Comparison Table - (*12 sqm Room*)		
Insulation Type	**Insulation Depth (mm)**	**Room Area Lost (sqm)**
Aerogel	10	0.014 sqm
PUR	16.9	0.236 sqm
PIR	16.1	0.225 sqm
Mineral Wool	26.9	0.376 sqm
Batt Insulation	28.9	0.404 sqm
Cellulose	31.5	0.441 sqm

Material data taken from WUFI 5.2 material database.
Room Size - 3m x 4m (12 sqm) standard room with 225mm solid brick walls on all sides.
*10mm Aerogel U Value of **0.745 W/m2k** = Bench mark performance to be achieved.*

Table (4) Room area reduction comparison for each insulation material.

CHAPTER 3 RESEARCH DESIGN AND METHODOLOGY

A thorough research methodology is an essential element in planning any program of research. To ensure the successful completion of this work, a series of steps were followed.

A critical review of texts and background reading was undertaken to identify the gaps in knowledge, inform this research and develop appropriate research methods.

The data presented in this thesis was gathered during a 2 year Knowledge Transfer Partnership that involved the development of a new thin aerogel interior insulation product. This project was carried out with the assistance of the Technology Strategy Board. Raw materials, production processes and industry advice was provided by the A. Proctor Group Ltd. and academic advice and testing facilities were provided by Edinburgh Napier University.

Many of the tests carried out provided valuable data as to the behaviour of various materials when used together. A series of tensile & compression tests were completed with a view to verifying test results already determined by the product manufacturer and were required to confirm the validity of the previous data and the consistency of the test material supplied. Additional tests were completed on the product prototypes in the laboratory simulating the end use conditions the product would be subjected to. The results of which will be discussed later.

The aim of this research and testing is to determine the viability of a new aerogel based material, and the applicability of aerogel based insulation materials to retrofit construction projects.

Based on data gathered during the literature review, it is hoped that the suitability of aerogel as an insulation material for a variety of existing hard-to-treat envelope types will be reinforced and our understanding of its properties will be improved.

To investigate this, the research methodology will also involve a series of computer simulations to be completed using three distinct types of software; WUFI, BuildDesk, and the BRE U-Value Calculator. It is hoped that once completed, a comparison of the data from each simulation will identify variations and anomalies that may be explained by research done in other literatures or the results of laboratory testing as part of the KTP. This data may then be used to further calibrate existing Building Information Modelling data.

3.1 Literature review outcomes

The following three sections give an appraisal of the literature review, and outline how this review will direct the research going forward towards a successful outcome.

3.1.1 Scope

The scope of the literature review involved an appraisal of currently available insulation materials considered to be readily available “standard” materials; such as PUR, PIR, Cellulose and Mineral wool. The scope also included insulation materials that are of either higher performance or appropriate to a specific projects requirement such as VIP’s, Aerogels, DIM’s and PCM’s. These composite components exploit additional physical properties to assist in increasing their overall performance. For example, VIP’s make use of the additional thermal resistance of vacuums, DIM’s make use of moisture control to reduce the negative effects of prolonged high levels of relative humidity and PCM’s use the properties of latent heat to buffer thermal differentials and create temperature stability.

3.1.2 Gaps

Upon completion of the literature review, it was apparent that a significant body of research has been carried out on the physical characteristics of high performance insulations such as aerogel. Although this research examined the properties and characteristics of advanced superinsulators, they were not specific to particular types of traditional solid wall construction.

The literature review identified gaps in the current body of research in relation to the accuracy of computer modelling software to predict thermal performance outcomes when using superinsulators on traditional building envelopes. Other gaps were also identified such as a need to determine the effects if any, on moisture movement and any discernible relationships to the use of aerogels. Finally; the literature review did not identify a method of quantifying and utilizing any data from the use of aerogels in traditional building envelopes for the purposes of advancing the database for effective Building Information

Modelling. This information is of particular importance as it plays an important role in predictive performance based design.

3.1.3 Need

A number of approaches are required to be undertaken in developing a new aerogel product for application in the built environment; these include assessing the material encapsulation, structural bonding, and the consequential effects on heat transmission and vapour transmissivity.

The information gained from this research would seek to solve these issues while contributing to the overall product diversity of high performance insulation materials currently available to the end user.

With the built environment consuming approx. 40% of global energy demands for heating and cooling, the need for this research and other research projects like this have never been more necessary. Innovative research and ideas will allow our built environment to play its role in further reducing mankind’s impact on the environment and help to mitigate climate change.

3.2 Newly developed aerogel material

The core insulating material for the new building product proposed is a Silica Aerogel “*blanket*”. The material consists of 50% Polyester and 50% glass fibre fleece. The fleece material becomes infused with Silica Aerogel Nano Spheres, (*Sandberg et al 2013);* these nano spheres provide the insulation properties while the actual fleece material provides a structure for the nano spheres to bond to.

To successfully complete the research and development of the new product a material matrix was developed in which the properties and compatibility of possible additional component materials could be assessed. Factors such as weight, thickness, durability, fire resistance and cost were highly influential in the final selection. Once the selection had been narrowed down, a series of tests were carried out to attain data in relation to pull-off strength after adhesion to a wall, resistance to moisture, suitability for various internal finishes and also the overall thermal performance of the final product designs based on both computer simulation modelling and on-site trials.

Additional issues were also investigated such as appropriate application methods, cutting, filling and possible methods of damage repair. Extensive stakeholder interviews, reports and presentations were carried out in order to gauge what the industry response would be to this type of product and the data collected from this process has been used to feed into the current research.

3.2.1 Suitable encapsulation process

Various methods of bonding fabrics and thin plastic films were investigated, such as ultra-sonic welding, friction welding, electro-static welding and laser welding among others. These welding processes were rejected due to the requirement for high cost machinery as well as the additional processing involved. During the investigation period into suitable encapsulations, it was clear that any material deemed suitable for encapsulation would need to provide a full surface coverage without a bonding or sealing process. A liquid coating method of encapsulation was preferred to any sheet, film or fabric material as they require folds at the edges or bonded and sealed joints. A suitable coating material was identified which is discussed in Chapter 4.

3.2.2 Suitable surface laminate materials

The method of selecting a suitable surface laminate involved many months of research and compatibility tests. A final solution was reached which used a magnesium silicate board. Other materials that were investigated were thin thermoplastic sheets, thin high density fibre board, woven polypropylene, heavy gauge fire retardant cardboard and woven glass fibre sheets among many others. The suitability of each material was tested by a series of simple indicative tests for durability, flexibility, thickness and fire rating as well as cost per m^2.

3.3 Experimental testing of the newly developed aerogel

Experimental tests were carried out to identify any possible anomalies that may arise with the thermal and moisture performance of the aerogel insulation material due to the addition of the encapsulation. The process and results of this data collection and the rationale behind it is discussed in more detail in the following sections.

3.3.1 Hygrothermal performance

Understanding the hygrothermal performance of the new aerogel product will require an analysis of both the thermal and moisture properties of the product when viewed simultaneously as the same process. The presence of moisture in insulation materials can greatly affect their thermal conductivity as the moisture becomes a conduit through which heat energy can pass more freely.

While minimizing this process would normally be a relatively high priority, the same cannot be said for this process in traditional building envelopes. Traditional envelopes differ considerably from more modern envelopes in that their construction materials are more homogeneous and these materials tend to have a significant level of porosity and need to be able to “breathe”. This is a simple way of saying that the hygrothermal performance of a traditional building envelope is very different to that of a more modern envelope where the construction materials are not necessarily natural and are usually synthetic in nature.

Vapour Permeability Testing

Vapour permeability tests were undertaken on the encapsulated aerogel to assess the products “*breathability*”. This test was carried out by Mr Chris Sanders at Glasgow Caledonian University at the request of the A. Proctor Group Ltd. the method involved the following;

“*The test specimen is sealed to the open side of a test cup containing either a desiccant (dry cup) or an aqueous saturated solution (wet cup). The assembly is then placed in a temperature and humidity controlled test chamber. Because of the different partial vapour pressure between the test cup and the chamber, a vapour flow occurs through permeable specimens. Periodic weighing’s of the assembly are made to determine the rate of water vapour transmission in the steady state”.* These tests were carried out in accordance with *(BS EN ISO 12572:2001)*, and are available in Appendix A.

Moisture movement simulation

Moisture movement within a given building envelope will be greatly affected by the material components used to increase the performance of the envelope in question. Any moisture movement analysis within a structure would normally involve an analysis of issues relating to interstitial condensation and relative humidity. The simulations performed for this research will describe how super-insulating materials affect the moisture properties of various building envelopes such as those described in Chapter 2 Literature Review.

Moisture data will be simulated and analysed to determine the overall impact of moisture movement on the internally insulated existing wall types used in the thermal performance simulations. Once again, comparisons between wall types can be made, thus further informing the research on how the generally homogenous materials such as brick, stone and hybrid walls used in existing building envelopes will be affected by the aerogel material being used for this research (*Historic Scotland Technical Paper 10, 2011).*

3.3.2 Thermal performance testing

Thermal conductivity testing

To assess the possible performance of the new product it was necessary to determine the actual thermal conductivity of a control sample of the aerogel material which could then be tested against samples of the encapsulated aerogel in order to demonstrate which type of encapsulation offered the lowest increase in thermal conductivity. Tests were thus undertaken to evaluate the ability of the proposed encapsulated aerogel to thermally improve a solid wall to the minimum regulation requirements. These results are discussed in section 4.

Thermal performance simulation

This research will examine the impact on thermal performance an aerogel based super-insulator will have on the overall U-Value of existing building envelopes (composite walls incorporating the aerogel product). This will be done by performing a comparison of simulated data using the WUFI, BuildDesk**,** BRE U Value Calculator software on traditional building envelopes. This data will also be compared to empirical data acquired from testing actual wall samples identical to those used in the software simulations. The result of this research may demonstrate that aerogels can be used in conjunction with other insulation materials to boost thermal performance. The research could demonstrate that aerogel based insulation materials used as a stand-alone solution may also be adequate to provide the level of thermal performance required by the regulations and codes. There is of course another possible outcome from this research; it is possible that the research could show that aerogels are unsuitable for use in certain existing building envelope constructions.

One possible factor influencing this would be the calculated payback periods which will in turn depend on the cost of the insulation material, cost of installation, the cost of a unit of heating fuel, whether it is oil, gas or electricity or other such as a ground source heat pump for example. The important point to note here is that the research may identify the forms of existing building envelopes in which aerogels may be most effective. In order to accurately determine the payback period for the given thermal improvement, the research would also involve an in-depth cost analysis. In addition to this, a lifecycle and embodied energy amassment of each wall sample with the applied aerogel based insulation would need to be carried out (*Historic Scotland Technical Paper 13 ,2011).*

This research would seek to look in detail at three external wall types considered common solid wall construction in the UK. Timber frame construction would ideally be included due to the fact that this form of construction is traditional to the North America and Scandinavia as much as stone and brick are traditional to the UK and its inclusion will would demonstrate a wider level of applicability to retrofit construction projects but it is currently outside the scope of this research. *(Habitat for Humanity, US Construction Standards).*

Relationships between moisture movement and thermal performance may be identified and described in a way that will be either verified by or contradictory to results predicted by computer simulation modelling when compared to the data gathered for this research during the product development stage.

3.3.3 Descriptive Method of analysis

The research designs presented in the preceding sections incorporate both descriptive and experimental research. Descriptive analysis is used to describe data, using either percentages or a frequency to illustrate findings *(Naoum, 2013).* Relationships between parameters will be shown and assessed and are presented in section 4 and 6.

3.4 Interviews

3.4.1 Rationale

In the period from March 2012 to February 2014 a series of interviews were held in relation to the KTP research and development project which holds valuable information for the current research project. These interviews were held with individuals who represent the majority of the stakeholders that would impact the success and up-take of any new insulation product. The stakeholders represent Government bodies and Energy Companies who have offered their opinion on what aspects were considered to be important to them. This information is based primarily on realistic and practical requirements and demonstrates real-world needs as opposed to idealistic aims.
The following list identifies the contributors;

1. Glasgow City Council:
2. Scottish & Southern Energy
3. Change Works, Edinburgh
4. Historic Scotland

Appendix B, from B-1 to B-4 contains all of the items that were discussed at each interview. It is immediately apparent that there is a significant level of commonality between the points discussed at each interview. This fact was particularly useful as it clearly highlighted many points that stakeholders considered important and any new insulation measure would need to satisfy these needs.

3.4.2 Interview Sample Size and Questionnaire

The sample size taken for these interviews could be considered small, as it does not include input from other parties that could be involved such as contractors, installers and material stockists.
One important feature of the sample group is that they represent the most influential proponents of any new initiative and for any new material that may become part of a government scheme or other possible financing initiative; the members of this sample group are key players. In terms of the values that could be placed on their expertise and influence it is fair to place greater value on

their input than less influential contributors such as installers or material stockists.

3.4.3 Questions

Prior to the interviews taking place, a set of interview questions was prepared in which the aim was to gain feedback on items that were deemed critical to the uptake of the new product. The questions that were asked were almost entirely related to the size, costs and performance of the product under development. During the preparation for the interviews it was initially suggested that greater values could be gained if the questions were tailored to the specific stakeholder, but after discussion it was clear that this approach would yield a high level of variance in the responses. As a result, the same questions were asked of each stakeholder in an effort to allow the qualitative data to be quantified. This would allow for a comparative analysis of the data received from each stakeholder.

3.4.4 Method of analysis

The research designs presented above incorporate both descriptive and analytical research. Descriptive research allows us to make simple inferences based on a counting exercise, while analytical research examines the difference within groups in order to detect patterns and relationships between variables . Inferential analysis will be used to compare results for different parts of the sample and provide a statistical significance test of the difference between proportions *(Naoum, 2013).* The parametric test (t-test) was identified as suitable to compare the difference between the mean scores of two samples and was therefore used for the analysis.

CHAPTER 4 TESTS RESULTS, INTERPRETATION AND ANALYSIS

This chapter will discuss the results of a wide variety of tests that were carried out during the two-year research project. These results were obtained from indicative, laboratory and computer simulation models, all of which will be discussed in detail in this section and also in section 5.

4.1 Experimental and Indicative Testing

Indicative testing was carried out at the A. Proctor Group's Dunkeld road facility in which a temporary lab had been set up to carry out tests, analyse the results and catalogue and store component materials. These materials were sourced as possible product components dependant on their suitability based on the various test results.

Laboratory testing took place at Edinburgh Napier University for easy access to testing machinery, electronic measuring devices and the environmental chamber. An additional benefit from using the university facilities was access to members of staff with relevant expertise.

Additional laboratory testing was carried out via secondary sources in situations where the necessary equipment was not readily available; in these situations assistance was sought from Glasgow Caledonian University and Aspen Aerogels Inc.

The following list outlines the necessary testing that had been carried out to gain a complete understanding of the characteristics of the silica aerogel base material and also how these characteristics varied when combined with other materials considered to be candidates for components of the final product.

1. Tensile and Compression tests of the base silica aerogel blanket
2. Pull-off tests on the encapsulated aerogel blanket
3. Thermal conductivity tests on the encapsulated aerogel blanket
4. Moisture vapour transmission tests on the encapsulated aerogel blanket
5. Environmental chamber tests on various prototypes at different stages of completion.

The data gained from the indicative and laboratory tests described above were used to determine the focus and direction of the research but also to generate accurate empirical data that would directly contribute to the accuracy of the computer simulation models that would follow.

4.1.1 Tensile and Compression Testing

The tensile and compression tests were performed to verify the material characteristics described by the available Aspen Aerogels Inc. literature; these properties are outlined in Table 5 below.

Material property	Property measurement
Thermal conductivity	0.014 – 0.015 W/m.K
Dimensional stability	1%
Tensile strength parallel to faces	200 kPa
Tensile strength perpendicular to faces	100 kPa
Compressive stress	80 kPa at 10% deflection
Fire resistance	EN C-s1, d0

Table (5) Aerogel physical properties (Slovenian National Building & Civil Engineering Institute, 2012)

The rationale for bringing the above data into question is due to compressive forces being exerted on the raw silica aerogel blanket material for extended periods of time. The raw material is manufactured in Massachusetts in the United States, and then shipped to various locations in the US and other parts of the world. The material is provided by the manufacturers in large rolls; therefore, with the silica aerogel blanket having a density of approx. 150kg / m^3 and approx. 50 linear meters per roll, it was necessary to determine if sustained compression had any effect on the physical integrity of the material.

The tensile and compression tests first involved selecting a roll of material at random from which twenty (20) sample pieces of the silica aerogel material would be cut. These sample pieces were taken from the central portion of the roll; each piece measured 100mm x 100mm x 10mm. Ten (10) pieces were selected for tensile testing and the remaining ten (10) pieces for compression testing.

These tensile tests were carried out using a 50kN load cell sensor attached to the universal testing machine. Load sensors such as a 2kN or 5kN sensors would have been ideal as they would have produced a better load resolution, the 50kN sensor was the only one available at the time of testing.

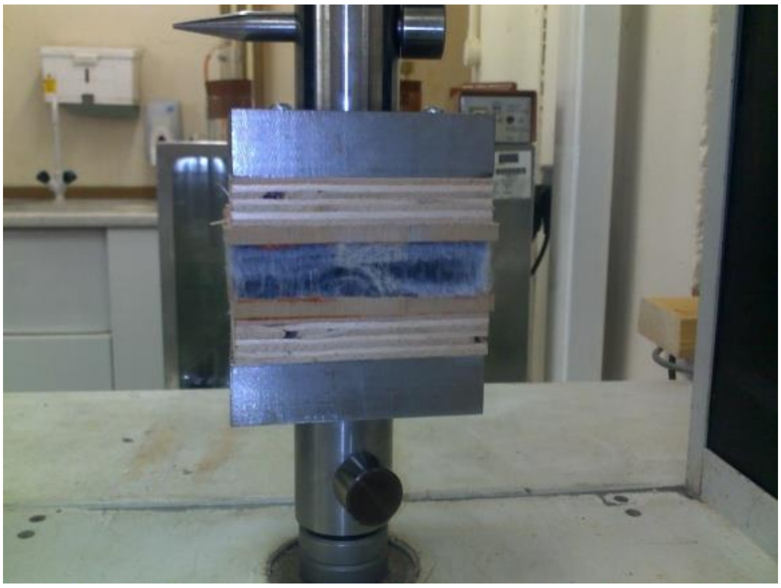


Fig (2), Tensile testing of an aerogel sample.

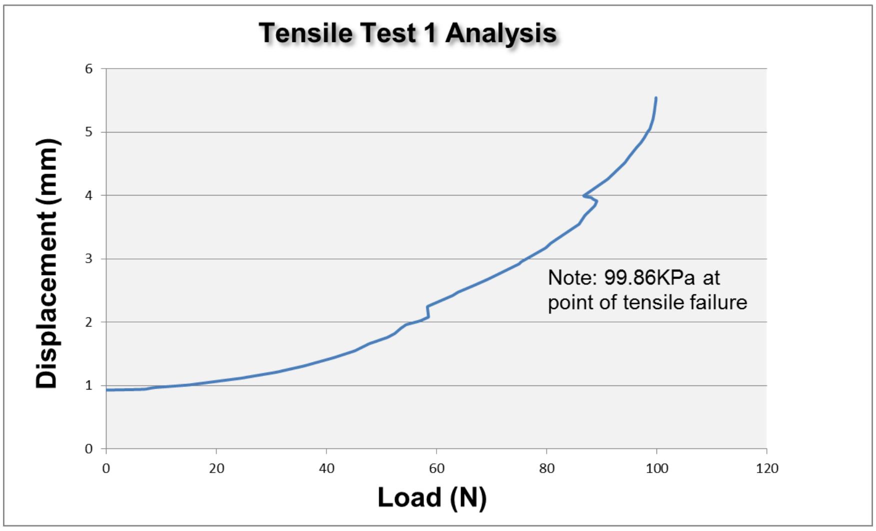
Fig. (2) above shows a typical sample undergoing a tensile test. The aerogel material was adhesively bonded to 8mm plywood plates on both faces of the aerogel blanket. The adhesive used to bond the aerogel material to the ply wood was manufactured by Intexa and care was taken to ensure that the adhesive could surpass the expected force required to delaminate the aerogel blanket. Table 6 demonstrates the amount of force applied perpendicularly to the face of each sample immediately prior to sample failure.

Aerogel - Tensile Test Results										
100mm x 100mm x10mm Sample Dimension										
Sample No.	1	2	3	4	5	6	7	8	9	10
Load (N)	99.86	111.14	101.42	103.17	127.36	123.36	119.65	116.97	117.11	118.2
Displacement (mm)	5.69	6.2	4.52	3.44	5.29	4.68	5.62	5.93	4.57	4.88

Table (6) Tensile test results for all ten samples.

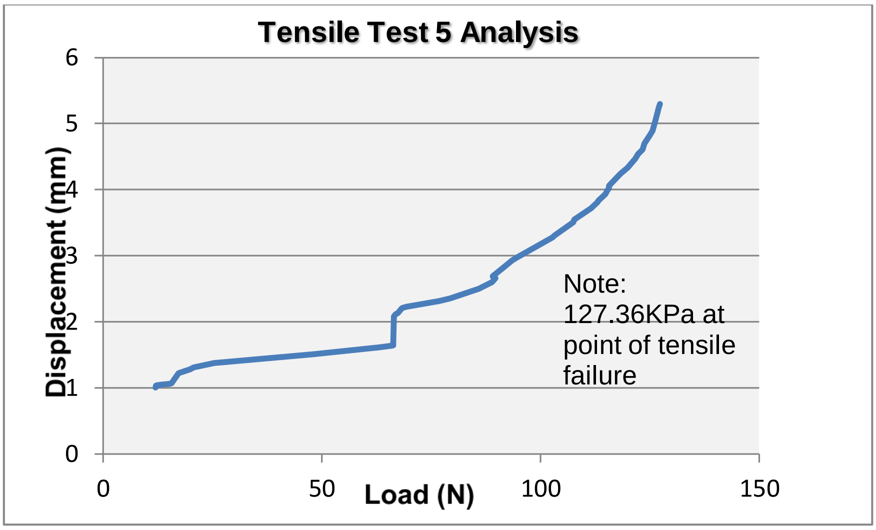
This table demonstrates that on average the samples performed in accordance with the information supplied by the manufacturer.

One interesting feature of the tensile testing is apparent when looking at the data in the form of a graph. Fig (3) to (5) show three sample graphs which show “jagged” edges to the curve in similar locations. The most plausible explanation for this is the delamination of the same layer present in each sample.



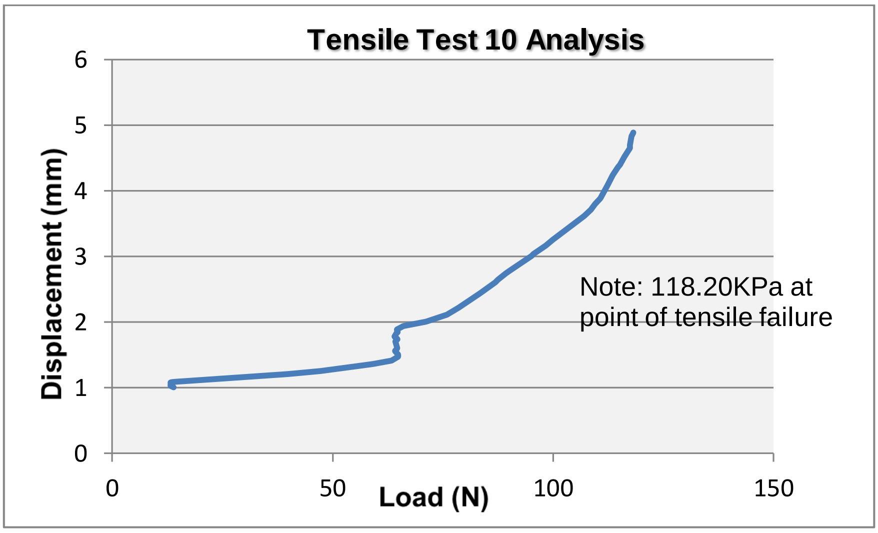
Note: 99.86KPa at point of tensile failure

Fig (3), Graph showing anticipated material failure.



Note: 127.36KPa at point of tensile failure

Fig (4) Graph showing material delamination point



Note: 118.20KPa at point of tensile failure

Fig (5) Graph of similar delamination point in a different sample.

The compression testing stage was significantly more complex than the tensile tests as an attempt was made during this stage to measure possible differences in compression over the surface area of the sample. It was considered possible that the samples may experience differences in compression due to varying levels of material density in some areas and the research may have to take this into consideration when analyzing the results; however, the variations observed were so small they were considered to be negligible.

Table 7 below shows the amount of force required to compress each sample as close to one (1) mm as possible. When this level of compression was achieved the tests were stopped, according to the manufacturers information, the aerogel blanket should be capable of resisting 100KPa of pressure with not more than 10% reduction on thickness. In this case the sample was 10mm thick hence the 1mm max displacement. The aerogel blanket exhibits a level of hysteresis, and therefore the measurements taken were from the point at which the load sensor began to detect compressive resistance from the material.

Aerogel - Compression Test Results										
100mm x 100mm x10mm Sample Dimension										
Sample No.	1	2	3	4	5	6	7	8	9	10
Load (N)	1000	990	988	990	990	1561	1517	1505	1492	1717
Displacement (mm)	1	0.97	0.94	0.9	0.94	0.98	0.98	0.98	0.98	0.96

Table (7) Max. load and displacement values for compression test results.

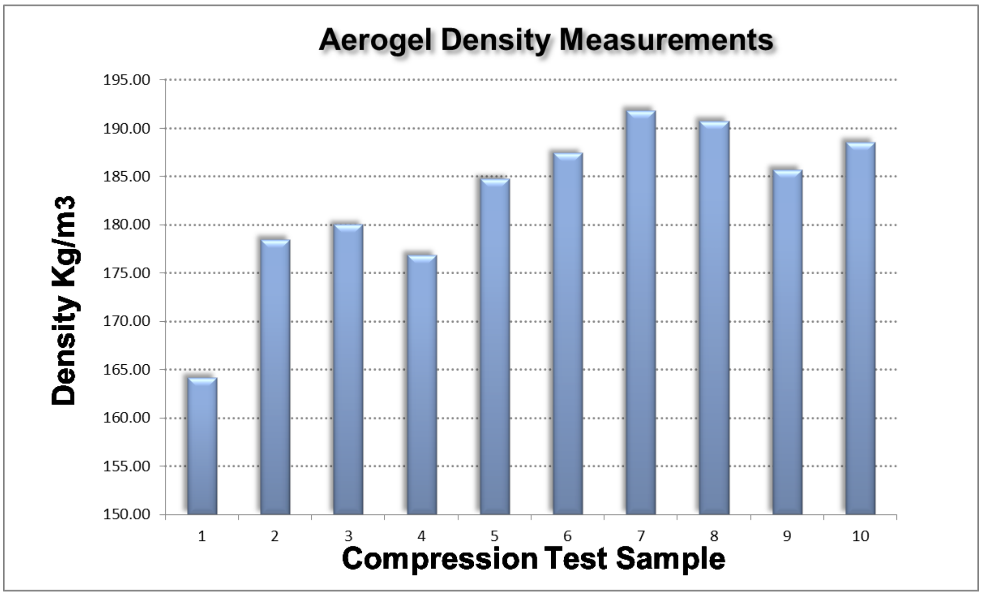


Fig. (6) Density measurements of each compression test sample.

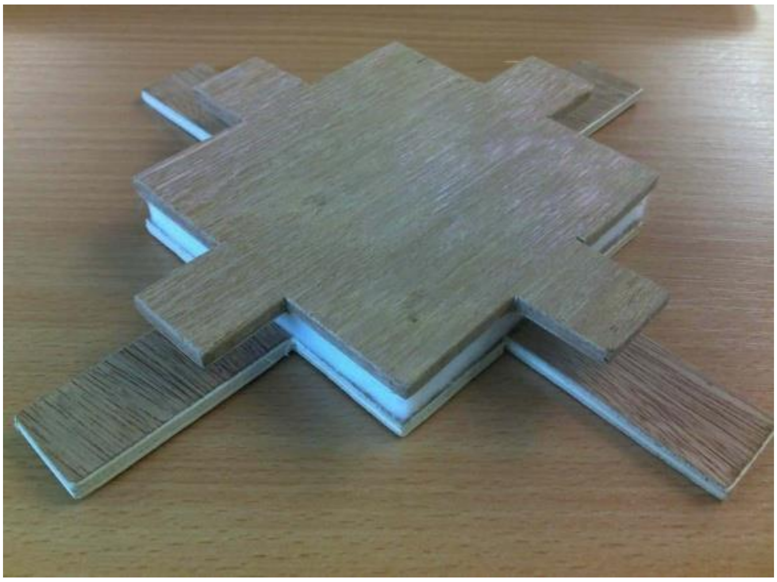


Fig. (7) Sample of aerogel blanket for compression testing

Fig (8) Compression test apparatus with measurement transducers.

There is an obvious correlation between the data shown in table 7 and fig (6), when both sets of data are compared it can be seen that as the sample density increases the compression force also increases, this is to be expected.

Fig. (7) shows a typical compression test sample with plywood plates designed to accommodate transducer sensors. Fig (8) shows a typical compression test sample in the testing machine with the transducers attached. This process was set up for each individual test sample. Once the characteristics of the aerogel blanket material were confirmed to be consistent with the manufacturer's information, the next step involved sourcing suitable methods of mitigating some of the issues that arise in handling the aerogel blanket.

4.1.2 Indicative plasterboard pull-off tests

Information on sourcing a suitable encapsulation for the silica aerogel blanket can be obtained from the accompanying research paper in Appendix A.

Once an appropriate encapsulation material had been sourced, further testing was completed on the base aerogel material to determine how the encapsulated silica aerogel blanket would perform in a real-world scenario.

To determine this, a series of indicative tests were performed. These indicative tests involved adhering samples of the encapsulated aerogel material to a variety of different surface types that would simulate the environment where the material would actually be used.

Surface finishes such as various types of paint commonly applied to interior walls were used, these consisted of gloss, eggshell, matt and vinyl paints.

Paper finishes consisted of 1200 gauge lining paper, woodchip paper, embossed paper and vinyl paper.

The make-up of each sample was identical with the only difference being the adhesive used to bond samples to the prepared surface type. Each test sample consisted of a 200mm x 200mm x 10mm piece of silica aerogel blanket fully coated with the FP 1908 series of latex encapsulation coating. After the latex encapsulation coating had dried, a 200mm x 200mm x 10mm OSB cover plate was adhesively bonded to the face of the encapsulated aerogel using a silicone based adhesive. The silicone adhesive was used to bond the cover plate to the coated aerogel because according to the manufacturers specifications, the bonding strength of the adhesive was expected to easily surpass the max force the coated aerogel could take and the purpose of these tests was to determine the maximum force required to delaminate the encapsulated aerogel.

An additional product of these tests would be an evaluation of the bond strength between the adhesives and the different surface finishes. The results of these tests are described in table 8.

Fig (9) below shows the main test board with two samples of painted finishes for both types of adhesive being used. The paper finishes were also sized for two coated aerogel samples, each using a different adhesive.

Fig (10) shows each of the 16 coated aerogel samples fully prepared and bonded in position, ready for testing.

Fig (11) shows a sample just prior to testing, a steel hook was set in place and a scale was used to measure the force required to delaminate the sample.

Fig (12) shows a typical test sample after delamination, one interesting feature of this image is that the sample adhered very well to the painted surface, this was the desired result.


Fig. (9) Various surface types for pull-off tests.


Fig.(10) Mounted samples ready for testing.

Fig. (11) Sample prior to test.

Fig. (12) Destructive testing of samples.

Plasterboard Pull-Off Test Results				
Sample No.	**Surface Finsh**	**Adhesive Type**	**Failure Type**	**Failure Force (N)**
1	Gloss paint on plasterboard	Silicone	Latex failure	315
2	Gloss paint on plasterboard	Insta-stik	Latex failure	315
3	Matt paint on plasterboard	Silicone	Latex failure	295
4	Matt paint on plasterboard	Insta-stik	Latex failure	325
5	Eggshell paint on plasterboard	Silicone	No Failure	345 (Max)
6	Eggshell paint on plasterboard	Insta-stik	No Failure	345 (Max)
7	Vinyl Silk paint on plasterboard	Silicone	No Failure	345 (Max)
8	Vinyl Silk paint on plasterboard	Insta-stik	Partial Failure	325
9	Woodchip wallpaper	Insta-stik	Partial Failure	345 (Max)
10	Standrad 1200 guage lining paper	Insta-stik	No Failure	345 (Max)
11	Embossed wallpaper	Insta-stik	Latex failure	345 (Max)
12	Vinyl wallpaper	Insta-stik	Latex failure	275
13	Woodchip wallpaper	Silicone	Adhesive failure	275
14	Standrad 1200 guage lining paper	Silicone	No Failure	345 (Max)
15	Embossed wallpaper	Silicone	Latex failure	295
16	Vinyl wallpaper	Silicone	Latex failure	265

Table (8) Test results for each sample showing failure type where appropriate and maximum force.

Table 8 above describes the surface finish, adhesive type and force required to cause a failure of the sample integrity, in some cases only a partial failure was recorded and other samples showed no failure.

The maximum force that could be applied by the scale was 345 Newton's, once this forced had been applied the test was suspended whether a failure had occurred or not. 345N equates to approx. 35kg acting on the samples perpendicularly.

Excluding samples where a failure was not recorded, the average failure force was 310N, all of which were full or partial delamination of the silica aerogel blanket. Previous indicative tests showed that the aerogel delaminated at 100 to 150N, so these result demonstrate an increase in integrity due to the addition of the encapsulation coating.

Another important feature of these results is that each sample remained adhered to each of the surface types. This tells us that both adhesives types are highly effective at bonding the encapsulated aerogel surface. The previous tests did not involve encapsulated aerogel and each failure occurred at the point where the aerogel was in direct contact with the adhesive. This strongly suggests an increased delaminated strength due to the encapsulation.

4.2 Encapsulated Aerogel Characteristics - Experimental Test Results

4.2.1 Vapour Permeability testing results

The latex based encapsulation material was available in two forms; one called FP 1283 being the standard version of the material and FP 1908 being the less viscus version. It was known, based on early application tests that the standard version could be applied to the silica aerogel blanket and encapsulate the aerogel very effectively. The same application tests had then been carried out on the less viscus version and it was found that this version of the encapsulation was just as effective in successfully encapsulating the aerogel once dried. Drying time was another additional benefit of the less viscus FP 1908 version, as the reduced viscosity also reduced the drying time.

The silica aerogel blanket has a high level of breathability which coupled with its hydrophobicity, makes the material highly suited to retrofit applications where natural homogenous materials allow unrestricted moisture flow in both directions. The use of un-encapsulated aerogel would not inhibit this physical property and the aim would be to find an encapsulation that would have the least impact on this natural process, thus the following tests were conducted on both versions of the latex based encapsulation.

Vapour permeability tests on a sample set of the encapsulated aerogel labelled Series 1908 and 1283 were carried out with the support of Glasgow Caledonian University. Figure (13) and figure (14) below show the MVTR samples for both encapsulation materials.

Fig. (13) FP1908 MVTR test samples.

Fig. (14) FP1283 MVTR test samples.

Table 9 below shows the results of the MVTR tests carried out on the above samples and the vapour diffusion thickness for the two different versions of the same encapsulation material.

	Series 1908		Series 1283	
	Value	Standard Deviation	Value	Standard Deviation
Water Vapour Permeance (kg/s.m^2.Pa)	5.27E-10	7%	2.99E-10	5%
Water Vapour Permeability (kg/s.m.Pa)	4.43E-12	5%	2.54E-12	7%
Water Vapour Resistance Factor (-)	43.67	5%	76.41	7%
Vapour Diffusion Thickness (S_d value) (m)	0.37	6%	0.65	5%

Table (9) MVTR tests results (Glasgow Caledonian University)

In the bottom row it can be seen that test series 1908 has a diffusion thickness of 0.37 as opposed to test series 1283 which shows a vapour diffusion thickness of 0.65. Other than this variation, the fact that there are no other significant differences between both samples works to the benefit of the new aerogel product, this is because the original encapsulation material had all the required characteristics necessary to provide a robust encapsulation for the aerogel blanket.

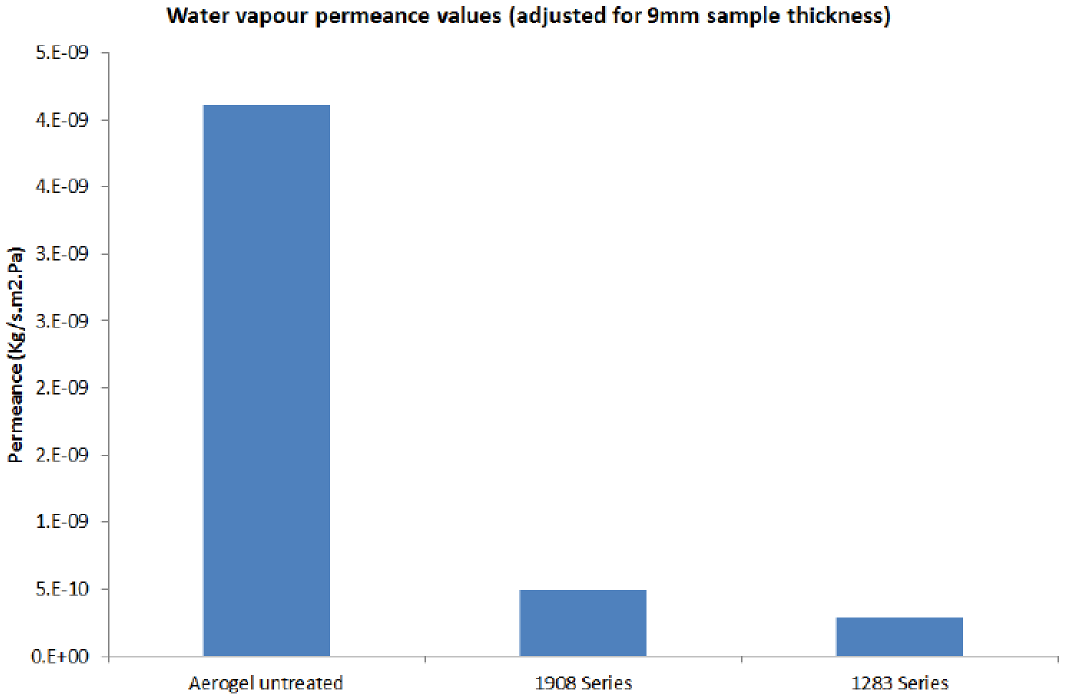


Fig. (15) Permeance comparison between coated and uncoated aerogel.

Fig (15) above identifies the difference between the breathability of the silica aerogel blanket and both encapsulation materials. As can be seen in table 9 the introduction of the encapsulation has a considerable effect on the permeability of the aerogel blanket. Because of this, it was necessary to determine what level of permeability a material would have to be classified as “breathable”. If we refer to section 6 for the analysis of the stakeholder interviews; the Historic Scotland representative stated that a breathable product would be desirable as traditional homogenous materials such as stone and brick exhibit bi-directional moisture flow and therefore a breathable product would be desirable to facilitate this natural process. According to *(BuildDesk 2013)*, vapour permeability is quantified as the “*perm*” value of a material. This is a measure of the vapour permeability of a material such as a vapour retarder located on the warm side of the insulation layer or a breather membrane located on the cold side of an insulation layer *(BS 5250: 2002 Annex E).*

A material is considered more breathable the higher the permeability value; generally a value greater than 1.

4.2.2 Thermal performance results

The minimum current U-value for solid wall refurbishment is 0.7 W/m^2.K. This value played an important role in the development of the new insulation product as it establishes the performance target to which the new product needs to comply as outlined in the Scottish Building Regulations, *(Technical Handbook - Domestic 2015)*. The next step in the analysis of the material properties was an examination of the effect that the encapsulation would have on the overall thermal performance of the silica aerogel material. This analysis is discussed in detail in the following section.

Thermal conductivity testing results

In addition to the vapour permeability tests in the previous section, a series of thermal conductivity (TC) tests were also undertaken in response to favourable indicative tests on other properties of the encapsulation such as the pull-off tests and MVTR tests discussed earlier. These TC tests were carried out with the support of Aspen Aerogels in their labs at Northborough Massachusetts, USA. The results are shown in table 10 below and indicate that both encapsulation materials tested; FP 1283 and FP 1908 did have an effect on the thermal conductivity of the silica aerogel blanket. The samples tested measured 100x100mm x 10mm thick and were coated to give the same level of coverage as the samples shown in fig (13) & (14) in section 4.2.1

Aspen Aerogel - Test Samples				
Coupon No.	**Encapsulation Type**	**Application Method**	**Pre Encapsulation Thermal Conductivity**	**Post Encapsulation Thermal Conductivity**
ES100164 FT2 1 ENG429 TAG3	FP 1283 BATCH 438 / 13	1 COAT ROLLED ON	18.00 mW/m-K	21.30 mW/m-K
ES100164 FT2 1 ENG430 TAG2	FP 1908 BATCH / LAB	1 COAT ROLLED ON	18.00 mW/m-K	20.00 mW/m-K

Table (10) Effects of the encapsulation on the thermal conductivity of the aerogel (Aspen Aerogels Inc)

In table 10 above, both pre-encapsulation control samples have a thermal conductivity of 18 miliwatts, while the post-encapsulation results vary by 1.33 miliwatts. The lower thermal conductivity of the FP 1908 encapsulation material can be explained by this material having a greatly reduced solids' content as well as a significantly lower viscosity than the FP 1283 coating. These test results demonstrate that the FP 1908 encapsulation has the least effect on the thermal performance of the aerogel. Based on these results, the FP 1908 material was the more suitable of the two samples tested.

When this information is taken in context with the results of the indicative pull-off tests and the vapor permeability tests, they show that the FP 1908 encapsulation material exhibits the same physical properties as the FP 1283 material but with the additional benefit of a lesser impact on the thermal performance of the aerogel, therefore it was for this reason that the FP 1908 material was selected as the primary encapsulation material moving forward with the research.

With the thermal conductivity tests complete, it is now possible to take the effect of the encapsulation into account when modelling the thermal performance of the composite material on a variety of wall types.

U-value calculations

Prior to simulation modelling of the behaviour of the encapsulated aerogel material in relation to heat and moisture flow, it was necessary to determine how the encapsulated aerogel material would affect the U-values for walls incorporating the aerogel product. The results of these calculations are shown in table 11 and were undertaken using the BRE U-value calculator version 2.03. Results suggest that the 18mm coated aerogel insulation product can meet the current UK regulatory requirements, a maximum 0.7 W/m^{2}K for an existing wall. To fully understand table 11 below, further explanation is required; the 13mm and 18mm “Wall Liner” refer to two distinct types of the silica aerogel product. The 13mm product is composed of 10mm of encapsulated silica aerogel with a 3mm magnesium silicate surface finish applied to the face of the encapsulated aerogel. The 18mm “Wall Liner” is composed of one layer of 10mm and one layer of 5mm silica aerogel bonded together using Intexa industrial adhesive, then fully encapsulated with the FP 1908 material, finally a single layer of 3mm magnesium silicate board provides the durable surface finish.

The Intexa industrial adhesive was applied using a spray gun resulting in randomly positioned “dots” of adhesive over the surface area of the un-encapsulated 10mm aerogel sample, this resulted in approx. 20% of the surface area of the aerogel being covered by the adhesive. This information is relevant to exclude the possibility of thermal variations due to the use and level of coverage of the bonding adhesive.

Wall Construction	Base Wall	13mm Wall Liner	18mm Wall Liner	Units
225mm Brick	2.06	0.86	0.67	W/m^{2}K
300mm Brick	1.72	0.78	0.63	W/m^{2}K
600mm Stone	0.87	0.68	0.68	W/m^{2}K
Brick cavity- Unfilled	1.45	0.72	0.59	W/m^{2}K
Brick cavity- Filled*	0.58	0.41	0.37	W/m^{2}K

All walls 13mm plaster on hard with 2mm air gap

*Brick cavity wall with insulation assumed at 0.038W/m^{2}K

Table (11) U-value calculations for solid wall types

In Table 9 above it is clear that all 18mm “Wall Liner” aerogel products achieve the necessary level of thermal performance required by the regulations. The 13mm product fails to meet a maximum regulatory requirement of 0.7 W/m^{2}K in all types with the exception of the 600mm stone wall. The Base Wall result for the 600mm stone wall shows an uninsulated U-Value of 0.87 W/m^{2}K. This is significantly better than the other uninsulated wall types excluding the brick cavity – filled. It is clear from the data above that the thermal performance of the

600mm stone greatly assisted the thermal performance of the 13mm aerogel wall liner.

The most notable result in table 11 is the thermal performance of the 225mm (9”) brick wall with the 13mm aerogel insulation product showing a thermal improvement from 2.06 W/m^{2}K to 0.86 W/m^{2}K. The reason this particular result is important is that a 225mm solid brick wall is the most common wall type of all the types shown in table 11 in the UK. The thermal improvement shown in table 11 constitutes a 58% overall thermal improvement for this wall type, this is the maximum percentage increase in thermal performance for any of the uninsulated wall types using the 13mm aerogel wall liner product.

It should be noted that there is a significant increase in cost between the 13mm aerogel material and the 18mm aerogel material. This in turn raises an important question; does the energy saving cost benefit justify the use of the 18mm aerogel product or the 13mm aerogel product. The importance of this will be seen in Appendix C where the results of the energy cost savings for the 10mm aerogel material thickness are shown for various dwelling types.

In table 11, all the wall types shown were evaluated on the bases that they would be finished with 13mm plaster on hard with a 2mm air gap. This is important to note as the aerogel product will require a suitable interior wall finish to allow for satisfactory interior applications. The 2mm air gap is derived from the estimated thickness of the adhesive used to bond the aerogel material to the interior surface of the wall type. The installation guide which was prepared by the author during the KTP project stage describes the method of fixing for the product, which states that a continuous strip of adhesive should be applied to the perimeter of the aerogel product on the face to be fixed to the interior of the wall. This adhesive “boundary” effectively traps a film of air behind the encapsulated aerogel creating an additional layer that contributes to the thermal performance of the retrofit. If however the air behind the panel were allowed to move due to convection or air infiltration then the insulation properties of the air layer would be negated.

A 2010 SPAB report demonstrated that the actual differences between the thermal performance of upgraded traditional buildings and those calculated for the same buildings using Build Desk modelling software was overestimated in relation to the in-situ figure as demonstrated by Rye (2010). Based on this information, the U-value data shown in table 11 above may also be overestimated; confirmation of this may be gained from on-site test trials, but this type of testing is currently outside the scope of this research. A comparison however can be drawn between the Build Desk, BRE and WUFI software and this will be discussed in section 4.3 and chapter 5.

4.2.3 Environmental Chamber Tests on Sample Variations

On completion of the indicative pull-off tests, MVTR and thermal conductivity tests, the next step in determining the physical properties of the silica aerogel insulation material was to carry out a test on the material at different stages of completion. This was done to build up a complete over view of how each additional component affected the thermal performance while utilizing equipment similar to tests that were carried out and described in research conducted and identified in the literature review. These tests also resulted in data which described the performance of two different jointing methods, allowing the research to determine which method would be the most appropriate. To carry out these tests, the environmental chamber at Edinburgh Napier University was used. Equipment such as heat flux sensors, thermocouples, relative humidity sensors and data loggers were required to gather the necessary information. The test chamber consisted of a small insulated room with a timber wall sheeted in OSB dividing the room into two equal volumes, with one volume being heated.

Fig. (16) Sensor equipment during calibration.

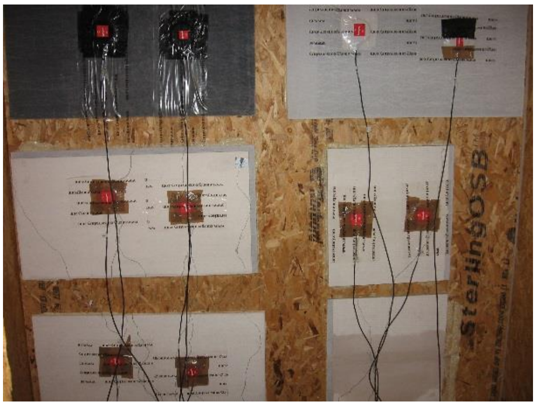


Fig. (17) Test samples & equipment in place

Fig (16) above shows the heat flux sensors in position prior to sample testing, the purpose of this initial set up of the equipment was to calibrate the sensors.

Once the calibration process was complete, the silica aerogel samples were set in position on the warm side of the test wall as shown in Fig (16), and each sample type and its position on the test wall within the test chamber was noted for future reference. The actual testing stage lasted approx. two weeks, during which time the data loggers recorded the relative humidity of the heated volume and thermal conductivity for each of the test panels within that volume.

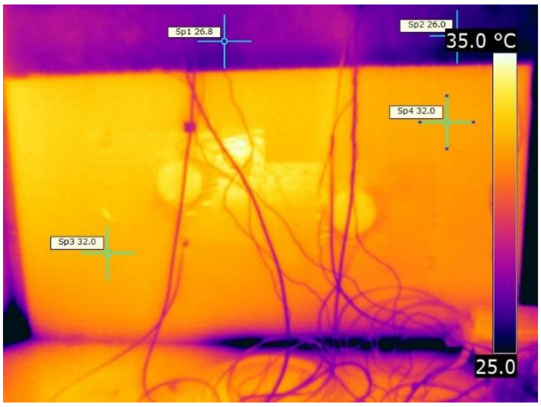


Fig. (18) Sensor equipment during calibration.

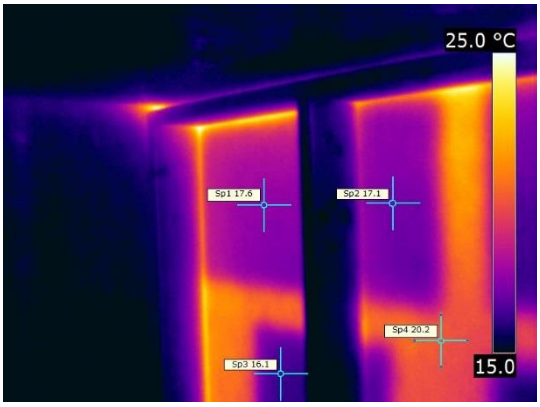


Fig. (19) Test samples & equipment in place

Thermal images were also obtained shown in fig (18) and (19) above, which demonstrate the thermal capability of the silica aerogel material. Fig (18) was taken on the heated side of the test wall; note the difference in temperature between the surface of the aerogel panel and the surface of the test wall. The test wall is cooler than the aerogel panel due the aerogel panel’s resistance to thermal heat transfer thus causing the surface of the panel to be higher than the test wall.

Fig (19) shows a thermal image taken from the cool side of the test wall, the conditions are the opposite of what is shown in Fig (18). The portion of the test wall that has been insulated is cooler than the uninsulated section as heat is allowed to pass with less resistance through the OSB sheeting as opposed to through the aerogel panels. Each of the heat flux sensors used for the environmental chamber tests were numbered and the average thermal conductivity recorded over the two week period was calculated and plotted on a graph shown in Fig (21). To help explain the relevance of the U-Value data in relation to the panel type tested, Fig (20) and table 12 have also been included.

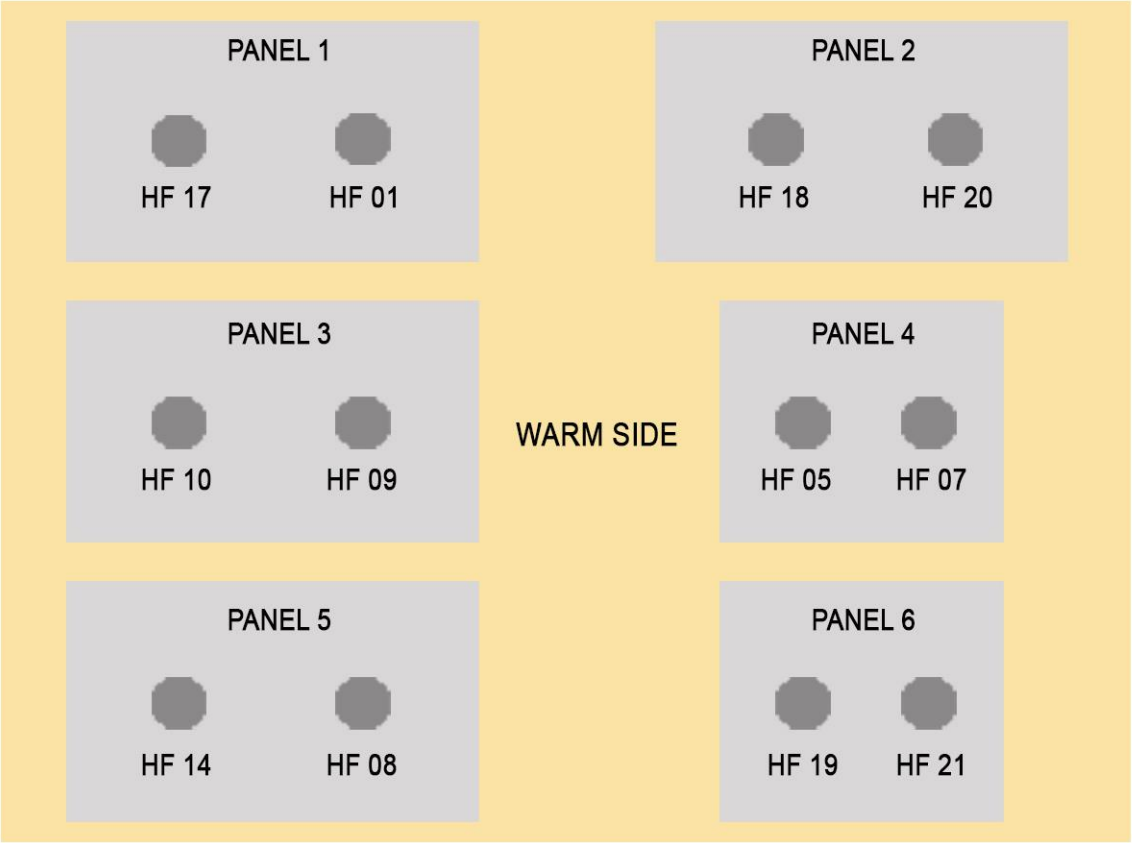


Fig. (20) Test panel and sensor location on the warm side of the test wall.

Environmental Chamber Thermal Transmission Testing		
U-value results		
Heat Flux	**Location / Panel Thickness**	**U-value (W/m^{2}K)**
HF17	Wall/ 10mm Aerogel	1.42
HF01	Wall/stud / 10mm Aerogel	1.34
HF18	Wall/stud / 10mm Aerogel	1.40
HF20	Wall / 10mm Aerogel	1.52
HF10	Wall / 10mm Aerogel	1.48
HF09	Wall/stud / 10mm Aerogel	1.40
HF05	Wall/stud / 10mm Aerogel	1.71
HF07N	Wall / 10mm Aerogel	1.79
HF14	Wall / 15mm Aerogel	0.99
HF08	Wall/stud / 15mm Aerogel	1.00
HF19	Wall/stud / 10mm Aerogel	1.43
HF21	Wall / 10mm Aerogel	1.51

Table (12) U-Value results for each test panel.

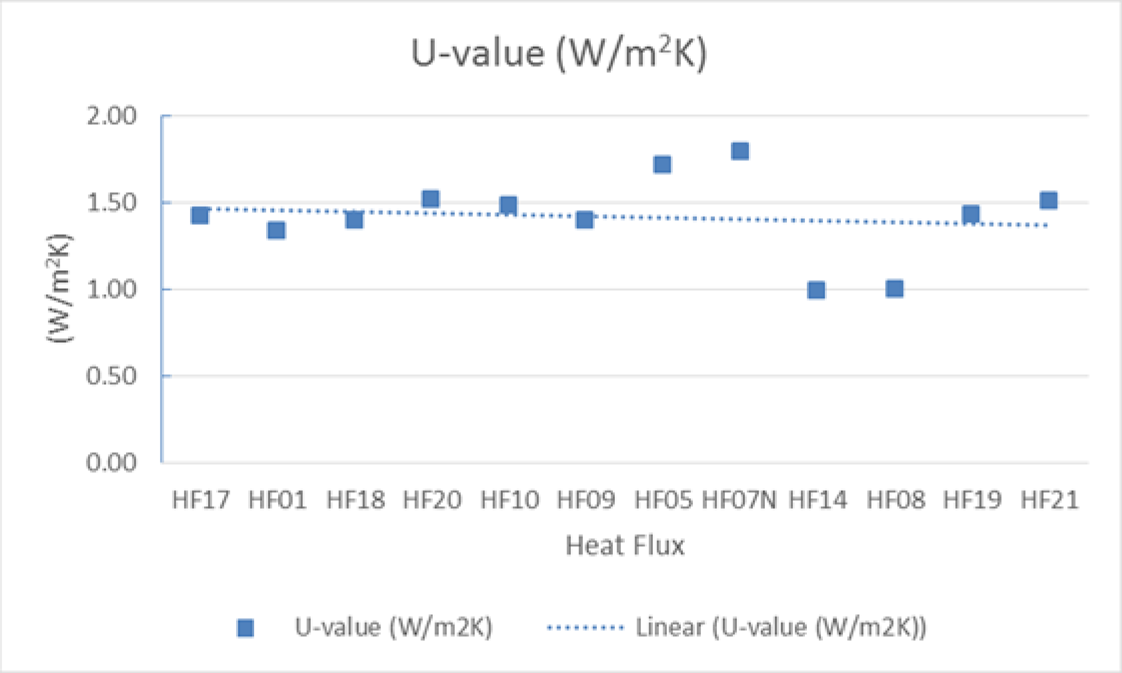


Fig. (21) Graph plotting each U-Value.

Fig (20) shows a graphic of the location of each of the test panels on the warm side of the test wall. Sensors HF 01, 05, 08, 09, 18 and 19 were placed to include the timber stud support to the wall in the data set, while all other sensors were placed to exclude the studs.

Fig (21) shows the U-Value results for each heat flux sensor, it is evident that the inclusion of the stud had an effect on the results due to the increased thickness at the stud location. Another interesting point to note is that the sensors HF 08 and 14 were both positioned on 15mm thick aerogel panels with sensors 08 being placed at a stud position. Here there is only a difference of 0.01 W/m^{2}K between both sensors on the 15mm aerogel panel. It is likely that the much smaller difference between both sensors is due to the thickness of the timber stud being almost completely negated by the thermal performance of the increased aerogel thickness, whereas the stud thickness had a greater impact on the thinner 10mm aerogel panel results. To support this, one simply needs to compare the difference between sensors HF 08 and 14 on the 15mm aerogel panels to any of the pairs of sensors on any of the 10mm aerogel panels, here the difference between sensors on the 10mm aerogel panels increases to almost 0.1 W/m^{2}K.

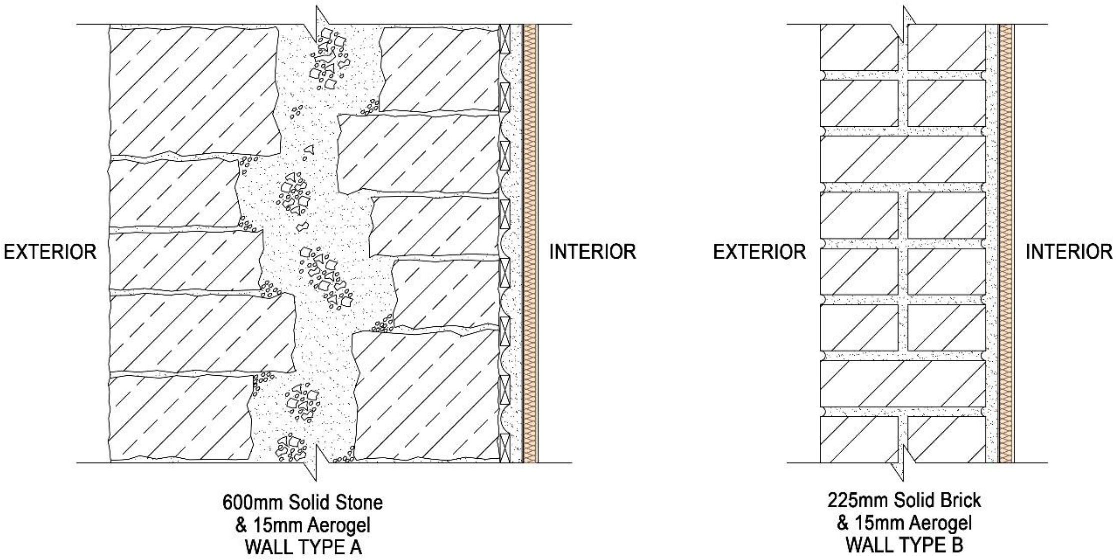
This demonstrates that with an increased thickness of aerogel insulation, any benefit from the structure of the wall decreases significantly.

4.3 Building fabric simulations results and discussion

One of the most important outcomes of this research will be a comparison and analysis of how the empirical data previously discussed would inform and influence results from simulation modelling. Using data from this research, the effects of the aerogel material when included as a retrofit insulation material on existing building envelopes can now be accurately modelled and compared to actual on-site test data. Based on information obtained during the literature review, the following existing wall types have been identified as being the most prominent forms of existing wall construction in the UK.

1. 225mm Solid Brick Masonry (*Internal plaster finish*)
2. 600mm Solid Stone (*Lath and plaster internal finish*)
3. 250mm Cavity Brick wall. (*With / without insulation*)

Item 3 above is a hybrid wall type which has been selected for simulation modelling as it is not only a common existing wall construction type but can also be modelled to include insulation within the cavity space.
Before an analysis of the simulation results are discussed, a clear understanding of each simulated wall sample is discussed to give a clear outline of what wall components were included in the simulation. This information will include a detailed description of each material component, dimensions and position. To further assist, a diagram of each sample simulation is also shown.



600mm Solid Stone
& 15mm Aerogel
WALL TYPE A

225mm Solid Brick
& 15mm Aerogel
WALL TYPE B

Fig. (22) Typical section through a solid stone wall and solid brick wall.

WALL TYPE A: This consists of a 600mm thick solid sandstone wall with approx. 40% of fines making up the core of the wall. This wall make up was identified during the literature review as being a common form of traditional solid wall construction. A lath and plaster finish has also been included in the simulation sample. It is likely that the original plaster would have consisted of horse hair to increase the durability and bond strength of the material but this material was not included in the simulation due to a lack of accurate data on its physical properties. In this absence of data, standard gypsum plaster was substituted for traditional plaster.

WALL TYPE B: During the literature review it was found that there are approx. five million homes in the UK of solid wall construction. The majority of these are constructed from uninsulated solid brick, typically 225mm / 9” thick. It is possible for the aerogel insulation to be retrofitted to this wall type whether or not the wall type includes a previous insulation retrofit.

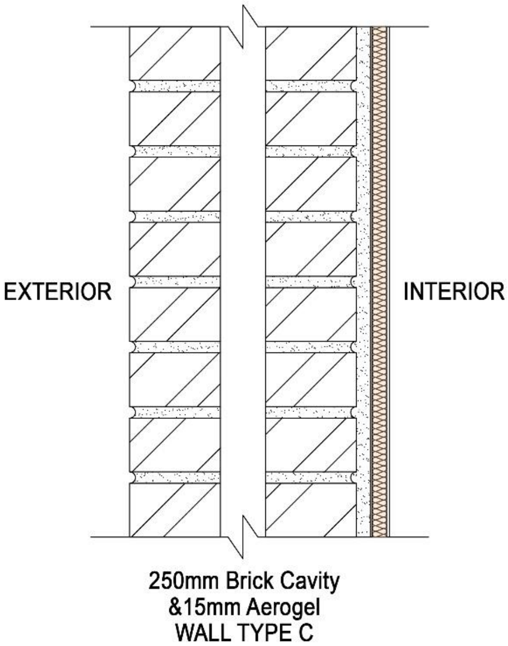


Fig (23) Typical section through a brick cavity wall (hybrid wall)

WALL TYPE C: this wall type has been simulated to include no cavity insulation as well as full-fill cavity insulation. In this construction method, the exterior brick acts as a type of rain screen and the cavity acts as a drainage layer. Once full-fill or partial fill insulation is introduced the thermal performance can be greatly improved. For this research both of these variations will be simulated to include 10 and 15mm aerogel.

4.3.1 Thermal performance of proposed systems

In evaluating the thermal performance of the proposed systems, three different types of software were used. These were the BRE U-Value Calculator v2.03 which was developed by the Building Research Establishment, WUFI Pro 5.2 developed by the Fraunhofer Institute for Building Physics and BuildDesk U 3.4. All three software programmes have the ability to determine the U-Value of the wall samples, as well as simulated moisture conditions. Once the simulations were completed they were then compared and evaluated.

The following information shows the physical properties of the materials used and the U-Value calculations for each wall sample without any form of additional insulation other than aerogel.

Material Physical Properties Data

In order to attain accurate results from each of the software simulations, the physical properties of each material used for each simulation was consistent and without variation. Values for the following material properties were sourced from data provided by the Fraunhofer Institute for Building Physics material catalogue in the WUFI software. The only exception to this was the thermal conductivity data provided by the environmental chamber tests and moisture vapor transmission tests discussed earlier in this thesis.

1. Material Thickness
2. Thermal Conductivity
3. Bulk Density
4. Specific Heat Capacity
5. Vapor Diffusion Resistance Factor (*Mu Value*)

Using the properties above, the following table demonstrates the data used for each material used in the thermal and moisture simulations:

Material	**Physical Properties**			
	Thermal Conductivity (λ)	Specific Heat Capacity (*Cp*)	Bulk Density (ρ)	Vapor Resistance Factor (μ)
Stone	1.8	850	2300	26
Brick	0.6	850	1900	10
Plaster	0.2	850	850	8.3
Calcium Silicate	0.05	920	230	2.9
Aerogel	0.017	1000	146	4.7
Air	0.047	1000	1.3	0.79
Vapor Retarder	2.3	2300	130	1

Table (13) Material physical properties for computer simulations

BRE U-Value Calculator v2.03			
Wall Type	Aerogel Thickness (mm) - Resulting U Value		
	No Aerogel (0mm)	Aerogel (10mm)	Aerogel (15mm)
600mm Stone	1.64 W/m^{2}K	0.77 W/m^{2}K	0.63 W/m^{2}K *
225mm Solid Brick	1.65 W/m^{2}K	0.77 W/m^{2}K	0.63 W/m^{2}K*
250mm Brick Cavity	1.34 W/m^{2}K	0.70 W/m^{2}K*	0.58 W/m^{2}K*
*Complies with Building Regulations for refurbishments			

WUFI Pro 5.2			
Wall Type	Aerogel Thickness (mm) - Resulting U Value		
	No Aerogel (0mm)	Aerogel (10mm)	Aerogel (15mm)
600mm Stone	1.65 W/m^{2}K	0.73 W/m^{2}K	0.58 W/m^{2}K*
225mm Solid Brick	1.75 W/m^{2}K	0.75 W/M2k	0.60 W/m^{2}K*
250mm Brick Cavity	1.40 W/m^{2}K	0.65 W/m^{2}K*	0.53 W/m^{2}K*
*Complies with Building Regulations for refurbishments			

BuildDesk U 3.4			
Wall Type	Aerogel Thickness (mm) - Resulting U Value		
	No Aerogel (0mm)	Aerogel (10mm)	Aerogel (15mm)
600mm Stone	1.61 W/m^{2}K	0.89 W/m^{2}K	0.73 W/m^{2}K
225mm Solid Brick	1.79 W/m^{2}K	0.93 W/m^{2}K	0.75 W/m^{2}K
250mm Brick Cavity	1.61 W/m^{2}K	0.50 W/m^{2}K*	0.44 W/m^{2}K*
*Complies with Building Regulations for refurbishments			

Table (14) U Value results comparison from all three types of computer simulator software

4.3.2 Moisture in proposed systems

In order to evaluate the effects of moisture due to the introduction of aerogel on the simulated proposed systems, a comparison of the simulation results was completed and will identify any agreement or disparity in the results. As with the thermal simulations carried out in Section 4.3.1, the BRE U Value Calculator v2.03, WUFI Pro 5.2 and BuildDesk U 3.4 software programs were used to simulate possible condensation risk and moisture surface accumulation in the proposed systems. Table 15, 16 & 17 below shows the results of these simulations; the significance of these results will be discussed in detail in Section 5.

BRE U Value Calculator v2.03				
600mm Stone Wall	Moisture Condition	Aerogel Thickness (mm)		
		No Aerogel (0mm)	Aerogel (10mm)	Aerogel (15mm)
	Interstitial Condensation	Not Present	Not Present	Not Present
	Surface Condensation	No Data	No Data	No Data
225mm Solid Brick Wall	Moisture Condition	Aerogel Thickness (mm)		
		No Aerogel (0mm)	Aerogel (10mm)	Aerogel (15mm)
	Interstitial Condensation	Not Present	Not Present	Not Present
	Surface Condensation	No Data	No Data	No Data
250mm Brick Cavity Wall	Moisture Condition	Aerogel Thickness (mm)		
		No Aerogel (0mm)	Aerogel (10mm)	Aerogel (15mm)
	Interstitial Condensation	Not Present	Not Present	Not Present
	Surface Condensation	No Data	No Data	No Data

Table (15) Moisture conditions predicted by the BRE U Value Calculator v2.03 (Based on an Edinburgh climate file)

WUFI Pro 5.2				
600mm Stone Wall	Moisture Condition	Aerogel Thickness (mm)		
		No Aerogel (0mm)	Aerogel (10mm)	Aerogel (15mm)
	Interstitial Condensation	Not Present	Not Present	Not Present
	Surface Condensation	Not Present No Mould	Not Present No Mould	Not Present No Mould
225mm Solid Brick Wall	Moisture Condition	Aerogel Thickness (mm)		
		No Aerogel (0mm)	Aerogel (10mm)	Aerogel (15mm)
	Interstitial Condensation	Not Present	Not Present	Not Present
	Surface Condensation	Not Present No Mould	Not Present No Mould	Not Present No Mould
250mm Brick Cavity Wall	Moisture Condition	Aerogel Thickness (mm)		
		No Aerogel (0mm)	Aerogel (10mm)	Aerogel (15mm)
	Interstitial Condensation	Not Present	Not Present	Not Present
	Surface Condensation	Not Present No Mould	Not Present No Mould	Not Present No Mould

Table (16) Moisture conditions predicted by WUFI Pro 5.2 (Based on the Kristiansand climate file)

BuildDesk U 3.4				
600mm Stone Wall	Moisture Condition	Aerogel Thickness (mm)		
		No Aerogel (0mm)	Aerogel (10mm)	Aerogel (15mm)
	Interstitial Condensation	Not Present	Present in Summer Months	Present in Summer Months
	Surface Condensation	Not Present	Not Present	Not Present
225mm Solid Brick Wall	Moisture Condition	Aerogel Thickness (mm)		
		No Aerogel (0mm)	Aerogel (10mm)	Aerogel (15mm)
	Interstitial Condensation	Not Present	Not Present	Present in Summer Months
	Surface Condensation	Present - Possible Mould Growth	Not Present	Not Present
250mm Brick Cavity Wall	Moisture Condition	Aerogel Thickness (mm)		
		No Aerogel (0mm)	Aerogel (10mm)	Aerogel (15mm)
	Interstitial Condensation	Not Present	Not Present	Not Present
	Surface Condensation	Not Present	Not Present	Not Present

Table (17) Moisture conditions predicted by BuildDesk 3.4 (Based on the Edinburgh climate file)

4.4 Concluding remarks

This chapter outlined issues with the core aerogel insulation material and methods of mitigating these have been highlighted through establishing the properties and limitations of the aerogel when used as a building material. Compression and tensile testing of the core aerogel material have demonstrated that the material exceeded the expected compression and tensile measurements by 10% to 15%. A product design suitable for adhesive bonding as opposed to the use of mechanical fixings was thus developed and demonstrated that the aerogel would not de-laminate under a significantly increased load such as those imposed by an encapsulation or additional surface laminate.

An appropriate encapsulation system using the FP1908 material was then sourced in light of these findings. Important properties (thickness, durability, fire rating and vapour permeability) of the FP1908 encapsulation were satisfied without significantly compromising any of the final products desired properties such as its thermal performance and fire rating.

A series of tests on the raw aerogel and encapsulated aerogel material using an environmental chamber were then followed by a series of software simulations in an attempt to simulate the performance of the encapsulated aerogel in a real-world environment. These simulations using a variety of software programs have provided preliminary theoretical performance results for this type of aerogel being encapsulated in this manner and applied to hard-to-treat walls. The minimal impact of the encapsulation on the thermal conductivity of the aerogel greatly assists in the availability of a more user-friendly high performance thin internal insulation product. The thickness of the final product shows that a maximum thermal performance can be gained for solid wall buildings with a minimal loss of internal room space, thus demonstrating its possible contribution to refurbishing hard-to-treat buildings and to the UK’s climate change strategy.

CHAPTER 5 COMPUTER SIMULATION RESULTS ANALYSIS

In order to understand the significance of the results, it is first necessary to outline important benchmark data which will determine the relevance of the results.

According to the current Scottish Building Regulations *Technical Handbook 6 - Domestic* for existing buildings; if the insulation envelope is being upgraded then it must be upgraded to achieve a U Value of not more than 0.7W/m^{2}K. This value is important as it sets the performance levels for the encapsulated aerogel and thus will determine the thickness of the encapsulated aerogel required to meet this U Value.

Previously in Section 4.2.2 table 10 it was shown that the thermal conductivity of the un-encapsulated aerogel was 0.018W/m^{2}K, and the thermal conductivity of the encapsulated aerogel was 0.020W/m^{2}K when using the FP 1908 coating. This increase in thermal conductivity due to the introduction of the encapsulation is important as it demonstrates that the encapsulation increases the overall thermal conductivity by 0.002 W/m^{2}K, this in turn affected the results of the computer simulations. The aerogel manufacturer updated their product literature in 2014 to show that their market aerogel product had a thermal conductivity of 0.015 W/m^{2}K. This is 0.003 W/m^{2}K less than the un-encapsulated sample tested in Section 4.2.2 table 10, therefore in the interest of maintaining accurate results, the thermal conductivity of the market aerogel product was used for the computer simulations with an additional 0.002 W/m^{2}K added to account for the increase caused by the use of the FP1908 encapsulation. Thus the thermal conductivity of the encapsulated aerogel used in the computer simulations was 0.017W/m^{2}K.

5.1 Calculated Performance and Regulatory Requirements

Table 14 in Section 4.3.1 identifies the calculated thermal conductivity of each wall type without aerogel insulation and also with the 10mm and 15mm aerogel insulation. Interestingly, both the BRE U Value Calculator v2.03 and WUFI Pro 5.2 show that precisely the same simulation samples satisfy the Scottish regulatory requirement. BuildDesk U 5.2 however calculates that only two of the 250mm brick cavity wall samples with 10mm and 15mm encapsulated aerogel meeting the regulatory requirement. There are two logical reasons why this is the case; *first* - variations in the values which were input into the simulation software would cause variations in the result, *second* - different calculation standards will invariably produce different results.

A *third* possibility would be the climate files used but climate data for the city of Edinburgh had been used for both the BRE U Value Calculator v2.03 and BuildDesk U 5.2, yet notable variations exist in their results. It is possible that climate data for the same city from two different sources may present variations in the results. This would require further investigation which is currently outside the scope of this research.

Prior to any calculations being carried out, care had been taken to ensure that the material properties entered in each simulation were identical to one another. In addition, it was not possible to get a climate file for the city of Edinburgh for use with the WUFI simulations, therefore a city with close climatic conditions which was also available as part of the WUFI software data base was chosen; this city was Kristiansand, Norway.

5.2 Interstitial and Surface Condensation Calculations

Tables 15, 16 and 17 show the results of the moisture properties of each of the three simulated wall samples. These wall samples have been simulated without aerogel insulation and also with the 10mm and 15mm encapsulated aerogel insulation. According to the BRE U Value Calculator v2.03 table 15, interstitial condensation has not been calculated to occur in any of the simulated wall types at any point of the year for the Edinburgh climate. This suggests that according to this model, there is adequate year round drying of the homogenous stone material and clay bricks for both the solid brick and cavity brick walls. The calculations were performed to BS 13788.

The results from the WUFI Pro 5.2 software also suggest that interstitial condensation is not an issue for any of the simulated sample wall types. These results from the BRE U Value Calculator and the WUFI software appear promising but caution should be expressed when interpreting the results from the WUFI Software, and these WUFI results in particular should be investigated further.

The BuildDesk U 3.4 moisture calculations show that interstitial condensation may be a problem when the 10mm and 15mm aerogel insulation introduced to the 600mm stone wall. The descriptive result states that this issue occurs during the summer months. Interestingly, the results also indicate the presence of surface condensation to the 225mm solid brick wall. Surface condensation to solid concrete and brick walls of a similar thickness are known to occur under the correct conditions. Unfortunately, this type of analysis has been difficult to obtain from the WUFI calculations due to the complexity of the results provided by the software and the BRE U Value Calculator does not specify surface condensation in its simulation results. Therefore, a more complete analysis of the moisture conditions in each wall type that can be crossed referenced between the three software programs could not be analysed in greater detail.

5.3 Concluding remarks

This chapter explored the results provided by three leading thermal and moisture analysis software simulators. It is clear from all three software simulators that the new aerogel insulation product has great potential to improve the thermal performance of existing Hard-to-Treat buildings. However, in contrast to the thermal benefits of introducing encapsulated aerogel to these buildings, it is also clear that care and forethought on an adequate ventilation system needs to be considered. The vapor permeability of the aerogel is conducive to bi-directional moisture flow which is beneficial to homogenous materials such as stone or porous materials such as brick. This property of aerogel may mitigate moisture issues when compared to other materials such as PIR or PUR insulations.

CHAPTER 6 INTERVIEWS RESULTS AND ANALYSIS

The analysis of the data provided by each stakeholder identified a variety of areas in which there was a high degree of similarity. These similarities related to the overall dimensions of the final product, others referred to the product warranty period, preferred method of fixing and preferred pay back periods to make the product feasible for government grants and schemes. It was expected that information relating to the thermal performance would be difficult to answer other than to say that ideally the product would need to meet or get as close as possible to achieving the minimum performance levels set out in the current building regulations for retrofitting existing buildings.

Breakdown of information sought from the project stakeholders included:

Specification

- Thickness
- Acoustic Properties
- Dimensions

Pricing*

- Cost per m^2
- Cost per product unit (.78m^2)

Product Certification

- OfGem
- BBA
- Other
- None

Warranty

- Yes / No
- No. of years
- Life expectancy

Other information was requested from each stakeholder regarding their input on accessories that would be considered useful to the end user and to the marketability of the new aerogel insulation product. This input varied extensively but can be viewed in the appendices.

6.1 Frequency Distribution

Info Type	**Stakeholder**	Thickness	Acoustics	Dimensions
Specification	Glasgow City Council	10mm	No	1200 x 600
	Scottish & Southern Energy	10mm	No	1200 x 600
	Change Works	10mm	No	1200 x 600
	Historic Scotland	10mm	No	1200 x 600

Table (18) Individual responses were in agreement with the product specification.

Table 18 above demonstrates each stakeholder's agreement with the calculated optimum design specification for the new aerogel insulation product. Each stakeholder firmly agreed that the insulation thickness was appropriate at 10mm. This high level of agreement was due to the cost per m^2 of the raw aerogel blanket insulation. Once thicknesses of 15 – 20mm were calculated it was clear that financing for this level of thermal improvement was not financially feasible due to lengthy payback periods, for further information on this refer to the payback calculations table in Appendix C, the costs relate to 2012 data. An additional point of interest based on table 18 above is the fact that the aerogel blankets acoustic properties did not merit any significant importance from any of the stakeholders. In relation to the dimensional specifications, feedback from each stakeholder again agreed with the design specifications. Historic Scotland had also suggested that 1000x1000mm panel could be desirable. The information provided here was highly influential in making an informed decision on the final aerogel product dimensions.

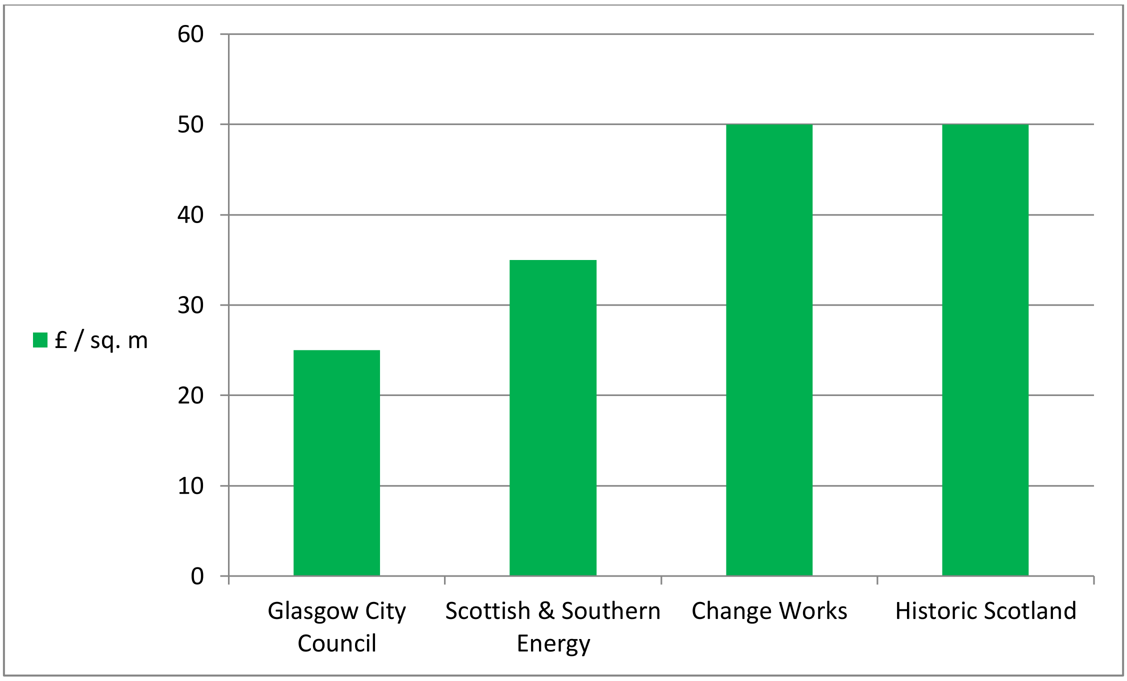


Fig. (24) Expected cost per product unit based on individual responses.

The stakeholders were also questioned on what they considered a competitive price point for the final product would be. The purpose of this question was to ascertain the feasibility of the product for its intended market and the information gained from the stakeholders at this point would allow a determination to be made to that effect. When we look at the histogram above it is immediately clear that there is a significant level of variation in what the stakeholders consider an appropriate price. To further analyse this trend in an attempt to understand why this variation may exist we need to consider who the stakeholders are and whom they interact with.

Glasgow City Council by the very nature of whom they are, and also Scottish & Southern Energy are heavily involved with an urban populace in which a significant proportion would fall into the low to medium income category. In addition, a portion of this population could also be considered at or below the fuel poverty line. With this information, it becomes more understandable as to why these stakeholders would favour a lower price point for the product. They are simply estimating the affordability of the new aerogel product to the consumer base they have experience in dealing with.

Change Works and Historic Scotland are both government-funded organizations whose purpose is to inform and assist in policy decisions and strategies. Therefore, the element of affordability is removed from their estimate, as they are not dealing directly with the end user. It is interesting to note however that their estimates are more realistic than Glasgow City Council, this may be because they do not need to consider the “human factor” and they have the ability to estimate a price point based on data such as material costs, labour costs and the estimated thermal performance improvement.

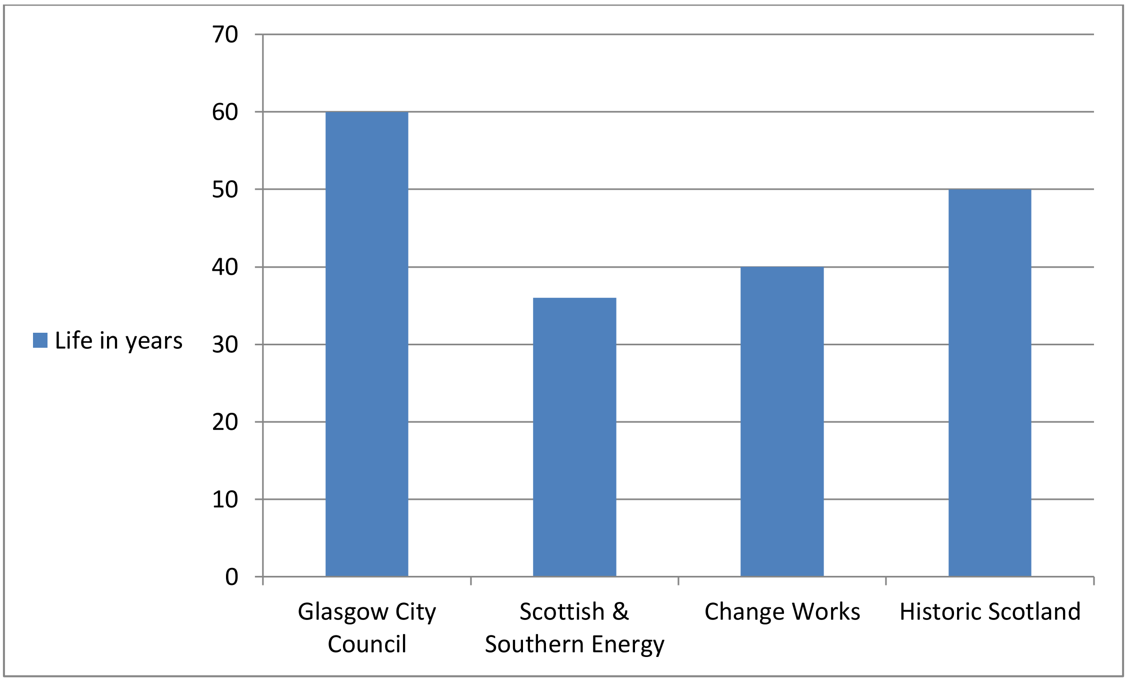


Fig. (25) Product life expectancy based on individual responses.

Fig. (25) above shows the stakeholders responses to what they perceive the ideal product life expectancy should be. As with Fig.(24) earlier, this histogram also demonstrates a significant variation in the desired product life expectancy. In an attempt to explain the variation in this case, it was necessary to identify a possible relationship between the question being asked here on product life expectancy and the previous question on cost. No significant relationship can be seen between the information provided by Change Works, Historic Scotland and Scottish & Southern Energy, there is however a disparity in the Glasgow City Council response, being a 60-year product life expectancy.

The underlying cause for such a high expectation must again relate back to the end user base that the stakeholder represents being low to medium income households with a portion below the fuel poverty line. Glasgow City Council is clearly of the opinion that any new aerogel based insulation product will have to be as cost effective as possible while providing maximum product life expectancy. It is very likely that the majority of these end users are in fact renters or rent-to-buy tenants. This consideration is important when attempting to interpret the information in Fig.(25) because the many of these types of properties fall under the jurisdiction of Glasgow City Council and they will be responsible for the funding of any thermal upgrades to any properties under their ownership, hence the low cost high life expectancy. None of the other stakeholders has this level of stake in end user properties. To prove this point, it would require a much wider sample consisting of additional City Councils and similar stakeholders to Historic Scotland and Change Works for a more accurate comparison, this however was outside the scope if this research.

In an attempt to understand the correlation between the estimated cost per unit and the desired product life expectancy, a measurement of dispersion between cost estimates and also between life expectancy estimates was calculated as follows:

$$\frac{\sum\left|x-\bar{x}\right|}{n}$$

Mean for unit cost = 40
Mean for life expectancy = 46.5

Once the mean for both the unit cost and the life expectancy was calculated, the next step was to calculate the standard deviation for both data sets individually using the formula below;

$$SD=\sqrt{\frac{\sum\left(x-\bar{x}\right)^2}{n}}$$

The results were as follows;
Standard Deviation for unit cost = 10.60
Standard Deviation for life expectancy = 9.31

These calculations are necessary as the results will be required during the inferential analysis. The next step will be to test the significance of the difference between both data sets; this will be discussed in more detail in the next section.

6.2 Inferential analysis

In completing the inferential analysis the following steps were taken;

1. The research hypothesis for this analysis is that there is no significant difference between the unit cost and the unit life expectancy.
2. The null hypothesis is that there is a significant difference between the unit cost and the unit life expectancy.
3. It has been determined that the T-test is the most suitable test for this analysis.
4. The calculation was carried out as described below.

$$t = \frac{\left(\bar{X}_1\right) - \left(\bar{X}_2\right)}{\sqrt[2]{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)}}$$

The T-test result for the unit cost & the life expectancy was 0.92, with 6 degrees of freedom this places the T-test result between the following statistical values: $0.5<P<0.05$. Based on this result we can conclude that there is no significant difference between the unit cost and the unit life expectancy; thus the null hypothesis does not stand true.

6.3 Limitations

The main limitation of the data obtained from the interviews is the sample size, which is quite small with data being gathered from four sources. Ideally, a larger sample size would have been sought but this was unrealistic due to the time constraints involved with the research project. One important point to make is that the four data sources that were chosen can be considered valuable and also having a good level of accuracy due to the nature of the sources being a combination of public and private entities responsible for either power supply, public housing or as advisors to government policies.

6.3.1 Collection method

The qualitative data collection method involved the prior preparation of a questionnaire with a set list of questions that would be asked of each interviewee. This would allow for a high degree of comparability between answers and thus allow for a more accurate analysis of the results.

6.3.2 Analysis

Based on the results it is apparent that even though the questions were consistent, the answers were variable to the extent that they were difficult to compare accurately. The qualitative data did provide interesting and valuable information, which was used to steer the research focus in an appropriate direction. The descriptive analysis identifies and explains the main points of the data provided and outlines some of the more prominent and reoccurring points. The inferential analysis involved a statistical comparison between the qualitative data obtained from each of the four data sources. The T-test analysis has shown that the data exhibits an appropriate level of agreeability to the hypothesis that a strong correlation exists between the cost of the product being developed and the life expectancy.

6.4 Concluding remarks

The information obtained from the descriptive and inferential analysis is valuable as it allows the research to draw conclusions that may assist in determining a final price point, thus the appropriate material thickness and thermal performance can be estimated more accurately before the product gets to market. This in turn will allow for more accurate payback periods to be calculated and thus the energy savings can be related back to the end user in real monetary terms.

CHAPTER 7 CONCLUSIONS

This research was conducted with the primary objectives of determining the applicability of aerogel fleece to 'hard-to-treat' buildings. Additional research objectives involved finding methods to resolve various issues with the aerogel material including; dust mitigation during cutting, application methods to existing wall surfaces, and determining the combined physical properties of all of the materials used in the final composite insulation product.

The approach involved a comprehensive understanding of the core aerogel material and its constituents. This involved some historical background research of the material and its development, a literature review of the current knowledge base for the material and a clear outline of what would be expected of the final composite insulation product when used in real-world applications.

A methodology was then formulated to create a systematic approach to the research and testing to be undertaken; and to achieve the aim and objectives of this research.

7.1 Conclusions on research objectives and questions

Silica aerogel has been shown to significantly improve the thermal performance of Hard-to treat walls. The usability of the aerogel insulation was also shown to be greatly improved when appropriately encapsulated and no adverse effects to the existing wall materials were identified because of the introduction of the silica aerogel insulation.

In answering the research questions, which form the focus of this thesis, silica aerogel was identified as the most suitable material based on criteria such as cost, thermal conductivity and current availability. Further testing provided additional initial evidence in support of the suitability of silica aerogel as a retrofit insulation for hard-to-treat walls. Questions were also raised in relation to industry opinions on the use of aerogel and it was found that in general, the various stakeholders involved were open to the use of new high performance materials such as silica aerogel.

7.2 Contribution to knowledge

Original contribution within the context of the presented research can be identified in the following sub-sections:

New aerogel encapsulation

Accurate data for future computer simulations & BIM analysis
Evidence for Regulatory Compliance

7.2.1 Aerogel Encapsulation

The successful encapsulation of the core aerogel material was one of the primary goals of this research; many options for a suitable encapsulation were examined. The test methodologies employed during the research allowed for a systematic process of elimination of unsuitable materials until the most suitable solution was found. Based on the literature review and research carried out during the Knowledge Transfer Partnership; the method of encapsulation for the core aerogel material used in this research had not been documented in any of the literature reviewed. This research proposes that the application of the FP 1908 material as an encapsulation to aerogel insulation is unique and the data collected on this process and the results from its impact on the thermal performance of the aerogel constitutes a valid contribution to knowledge.

7.2.2 Accurate data for future computer simulations & BIM analysis

Building Information Modelling (BIM), has its origins in the 1970's when a more holistic approach to building design with the inclusion of energy performance was sought. BIM was becoming a tool that designers could use to make more informed and effective decisions. Over-time the physical properties of many materials were added to BIM data bases for analysis and can now be found in market leading design software such as AutoDesk Revit, among others.
A goal of this research was to identify the energy performance properties of the new composite aerogel product which could be used as input for future retrofit building projects where the use of aerogel is a viable option for consideration. This research has been successful in demonstrating that the core aerogel material used in the research can be encapsulated with minimal impact on the overall thermal performance of the aerogel insulation. In addition, the thermal conductivity test results have defined the level of thermal performance that can be expected from aerogel insulation which has been encapsulated using the same or very similar material. This data could be used where building components which are considered 'hard-to-treat' can not only be insulated, but the energy performance of the building component can also be accurately simulated. This would prove beneficial within a BIM framework, particularly on

large-scale projects such as social housing refurbishments. In these situations, a cost benefit analysis based on calculated thermal performance improvements may be required prior to any work being carried out as well as better design decisions being made, which take the lifecycle of both the product, and building into consideration.

7.2.3 Evidence for Regulatory Compliance

In table 14 of section 4.3.1 of this research it was demonstrated that the 10mm and 15mm thick encapsulated aerogel had a satisfactory level of thermal performance based on the calculated U-Value data from the leading software simulation programs. The 10mm and 15mm encapsulated aerogel performed sufficiently well to satisfy the requirements of the current Scottish Building Regulations Technical Handbook - Domestic, Energy (2015), which states that any refurbishment to an existing wall must result in a final wall component U-Value of 0.7W/m^{2}K. This can be considered as initial evidence of regulatory compliance, but it must be corroborated by in-situ testing before it can be considered as definitive.

7.3 Research limitations

This research did not involve in-situ testing, full-scale laboratory testing, or on-site trials. These tasks were outside the scope of this research due to a limitation in access to materials and facilities. The majority of testing and materials supplied for this research was provided through a Knowledge Transfer Partnership between Edinburgh Napier University, A Proctor Group Ltd. and the Technology Strategy Board. The main research limitations are discussed in more detail in the following sections.

7.3.1 Wider Sample Range

One of the limitations of this research is the relatively narrow sample range in wall-types studied. However, solid stone, solid brick and brick cavity walls are more commonplace in the UK and Ireland and constitute a significant proportion of the existing residential building stock. Thus, it was considered a more efficient use of limited means and resources to concentrate the research in this area only.

7.3.2 Access to Software other than WUFI, BRE and BuildDesk

Access to a wider range of simulation tools and software might have added value to the study, but was either unavailable or financially unfeasible at the time this research was conducted. A broader set of simulated data would have been beneficial in terms of the subsequent empirical validation.

7.3.3 Access to test Equipment

Much of this research was conducted on a part-time basis and the author had limited access to the University laboratory facilities which was in-part due to the nature and demands of the Knowledge Transfer Partnership project and considerable changes to the author’s personal circumstances. The KTP project provided funding, materials and data which directly and significantly contributed to the completion of this research.

7.4 Recommendations

The following recommendations from the study are presented and which could enable tests to be recreated and confirmed independently under both on-site and laboratory conditions.

7.4.1 Actual On-Site Testing of Product

As a result of this research, it is recommended that any future research should involve the use of empirical on-site tests in addition to simulation data. This will allow for direct comparisons and correlations to be made between simulated and empirical data sets thus giving a more accurate description of the disparities or similarities between the data. These tests could also provide valuable data on actual moisture conditions within the wall types tested.

7.4.2 Full Scale Laboratory Testing of Product

It is also recommended that the final composite insulation product be fully tested by an independent testing agency to determine the physical properties and thermal conductivity and fire classification of the final product.

7.4.3 Input variations between simulation software and available material physical property data.

During the simulation stage of this research it soon became apparent that a disparity between the results from each simulation program could result from the data input required for each program. The reason for this is that WUFI Pro 5.2, for example, requires the addition of a porosity value for each material as a factor in its hygrothermal calculations. The BRE U-Value calculator v2.03 and BuildDesk U 3.4 does not require such information. Therefore, it is possible that thermal mass transfer which is considered by WUFI but not by the other programs would result in a noticeable difference between the WUFI results and the other software programs used. It would be a recommendation of this research that such disparities be investigated further.

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APPENDICES

Appendix A:
New thin aerogel for high performance internal wall insulation of existing solid wall buildings.

Appendix B-1:
Glasgow City Council - Stakeholder Meeting

Appendix B-2:
Historic Scotland - Stakeholder Meeting

Appendix B-3:
Change Works - Stakeholder Meeting

Appendix B-4:
Scottish & Southern Energy - Stakeholder Meeting

Appendix C:

Payback Data for 10mm Spacetherm (Based on 2012 Data)

New thin aerogel for high performance internal wall insulation of existing solid wall buildings

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ABSTRACT: Applications of nanotechnology in the form of high performing aerogel insulation are now widely used from space exploration to the oil and gas industry and in more recent years in the construction industry. Previous research has shown the merits of the new material as a high performing and effective solution which improves the thermal performance of complex building elements like solid walls. This research focuses on the development of a new aerogel insulation material aimed specifically at the retrofit market where space is limited and floor-to-ceiling heights are considered critical. The paper describes the testing being carried out on the application of coated aerogel samples designed to mitigate the thermal performance issues associated with solid wall buildings. Results are presented and their influences on the overall design of the new aerogel insulation material are evaluated. Results from MVTR, Thermal Conductivity testing and U-value calculations show that a maximum thermal performance can be gained for solid wall buildings with a minimal loss of internal room space, thus demonstrating its possible contribution to refurbishing hard-to-treat buildings.

1 INTRODUCTION

While new buildings can easily be designed to include energy efficient methods, the existing building stock creates an obstacle in reducing UK target carbon emissions due to their poor overall thermal performance. The upgrade in their thermal performance is therefore an important step towards a successful climate change policy which will include creating products that are suitable for domestic retrofit projects. Difficulties are however encountered when considering “hard to treat” dwellings which cannot accommodate easily cost effective fabric energy efficiency measures (Roaf et al., 2008). There are over five million traditional solid wall constructed dwellings in the UK (Palmer and Cooper, 2012) having little or no insulation, the majority built before 1919. In addition, there are a significant number of listed and protected existing buildings for which restrictions apply when considering alterations (Changeworks, 2008). This could be as a result of the buildings historical or architectural significance such as its designer, architectural style and materials used (Barnham and Crookshanks, 2006). There is thus a need to explore the development of new highly performing products and methods to insulate these existing solid wall dwellings.

According to the most recent building regulations in Scotland, England and Wales, (Department for Communities and Local Government, 2013; Technical Hand Book 6: Energy (2011), any retrofitted insulation measure must meet specific thermal performance standards. These standards clearly set out permissible U-values for solid wall buildings and in turn create a performance target for any new insulation product. The BRE CERT (2007) shows that if 0.5% of the existing solid wall homes in the UK were insulated using aerogel insulation products, it would result in a 25,000 tCO_2 emissions reduction per year or 750,000 tCO_2 over a thirty year period. This is based on a typical 225mm brick solid wall having a U-value of 2.1 W/m^2K and a 15mm thick aerogel insulation panel bringing the solid wall U-value down to 0.7 W/m^2K. The aerogel material itself has however several issues, ranging from dimensional tolerance and instability, lamination strength, hydrophobicity and excessive dust generation (Carty, 2013). A great concern is the mitigation of dust produced when the product is handled; hence the need to reduce this exposure. This paper evaluates available materials that could be used as suitable components for the creation of a new insulation product compatible with amorphous silica aerogel (I.S.G.S., 2011). It examines ways to appropriately encapsulate the raw aerogel with the objective to make it safer to handle and identify available surface laminates and surface finishes which would provide an appropriate level of fire protection, durability and flexibility with minimal thickness.

2 METHODOLOGY

A number of approaches had to be undertaken in developing the aerogel product for application in the built environment; these included assessing the material encapsulation, structural bonding, and the consequential effects on heat transmission and vapour transmissivity.

2.1 *Suitable encapsulation process*

Various methods of bonding fabrics and thin plastic films were investigated, such as ultra-sonic welding, friction welding, electro-static welding and laser welding among others. These welding processes were rejected due to the requirement for high cost machinery as well as the additional processing involved. During the investigation period into suitable encapsulations, it was clear that any material deemed suitable for encapsulation would need to provide a full surface coverage without a bonding or sealing process. A liquid coating method of encapsulation was preferred to any sheet, film or fabric material as they require folds at the edges or bonded and sealed joints. A suitable coating material was identified which is discussed in section 4.

2.2 *Suitable surface laminate materials*

The method of selecting a suitable surface laminate involved many months of research and compatibility tests. A final solution was reached which used a magnesium silicate board. Other materials that were investigated were thin thermoplastic sheets, thin high density fibre board, woven polypropylene, heavy gauge fire retardant cardboard and woven glass fibre sheets among many others. The suitability of each material was tested by a series of simple indicative tests for durability, flexibility, thickness and fire rating as well as cost per m^2.

2.3 *Thermal conductivity testing*

To assess the possible performance of the new product it was necessary to determine the actual thermal conductivity of a control sample of the aerogel material which could then be tested against samples of the encapsulated aerogel in order to demonstrate which type of encapsulation offered the lowest increase in thermal conductivity. Tests were thus undertaken to evaluate the ability of the proposed encapsulated aerogel to thermally improve a solid wall to the minimum regulation requirements. These results are discussed in section 6.

2.4 *Moisture Vapour Transmission Rate (MVTR) testing*

MVTR tests were performed to measure the vapour transmission rate of the proposed encapsulation. These tests played an important part of the research and development process as some encapsulation alternatives were shown to have high vapour permeability creating condensation problems. The information gained from these tests would thus determine the applicability of the proposed encapsulation to solid wall building elements.

3 AEROGEL PHYSICAL PROPERTIES AND LIMITATIONS

The core insulation material used in the development of this product is amorphous silica aerogel whose relevant properties are outlined in Table 1 below.

Table 1. Aerogel physical properties (Slovenian National Building and Civil Engineering Institute, 2012)

Material property	Property measurement
Thermal conductivity	0.014 – 0.015 W/mK
Dimensional stability	1%
Tensile strength parallel to faces	200 kPa
Tensile strength perpendicular to faces	100 kPa
Compressive stress	80 kPa at 10% deflection
Fire resistance	EN C-s1, d0

A series of tensile and compression tests were carried out on various aerogel samples to confirm their tensile and compression properties as shown in Figure 1 and 2. These tests demonstrated that the aerogel had typically between 10% and 15% higher resistance when compared to the data supplied by Slovenian National Building and Civil Engineering Institute (2012) for both compression and tensile stress. To carry out these tests, ten samples were used for compression testing while an additional ten samples were used for tensile testing. Each of these samples was taken from the same roll of material.

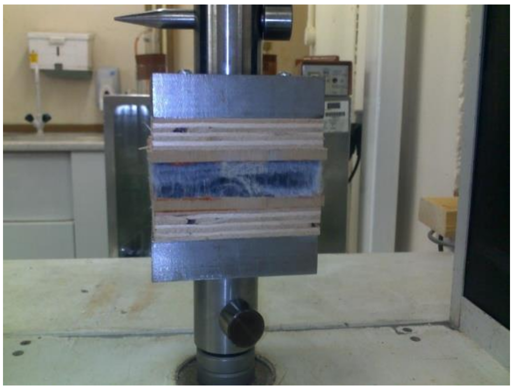

Figure 1. Aerogel tensile test in progress.

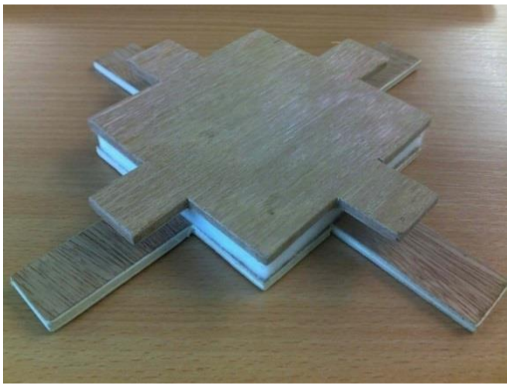

Figure 2. Compression test sample.

4 SUITABLE APPLICATION PROCESS FOR ENCAPSULATION

The properties of the aerogel mat effectively defined the materials suitable for use as an encapsulation. As outlined in section 1, the aerogel material produces excessive amounts of dust when handled and manipulated. The dust itself was classed as non-carcinogenic but was identified to potentially cause mechanical irritation of the upper respiratory tract (Spaceloft MSDS, 2011). As well as reparatory issues, the aerogel was found to be highly hydrophobic which can cause drying of the skin and could dry out lubricated machine components during processing. All of these factors contributed to the need to research a suitable encapsulation system. There are two main issues of interest in researching a suitable aerogel encapsulation system; (1) material type and (2) application process. The aerogel raw material has a high level of flexibility which was deemed to be a desirable property as it would not be restricted by the introduction of an encapsulation. According to the Slovenian National Building and Civil Engineering Institute (2012), the aerogel has a fire rating of EN C-s1, d0. Any encapsulation material would thus be required to maintain or improve the fire rating of the aerogel product.

The application process was also considered at this stage. From a mass production aspect, the application process must be as efficient as possible for manufacturing and labour intensity as well as financially. With this in mind, the most appropriate means of application identified were as follows;

a. Spraying
b. Dipping
c. Rolling

The FP 1283 coating material, which was originally developed as a fire retardant coating for woven fabrics, was originally identified during a visit to Formulated Polymer Products Ltd, Manchester in June 2012. A less viscous version of the FP1283 coating known as FP1908 was later acquired and was indicatively tested as an aerogel encapsulation. The new encapsulation system was investigated for its suitability and application considering the three applications stated above.

a *Spraying*

Many attempts were made to spray the various materials identified during the research stage onto the aerogel substrate. It was identified that aerogel fleece materials have a hair-like surface texture. Figure 3 below shows a magnified image of the aerogel surface with the visible hair-like filaments. Spraying this surface was shown to be extremely difficult as the fibres do not allow the sprayed coating to achieve a full surface coverage.

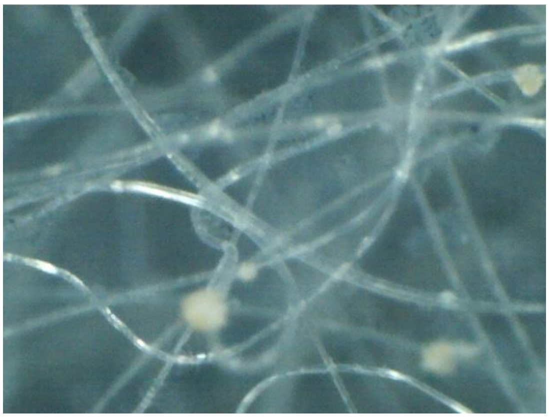

Figure 3. Magnified image of the aerogel surface.

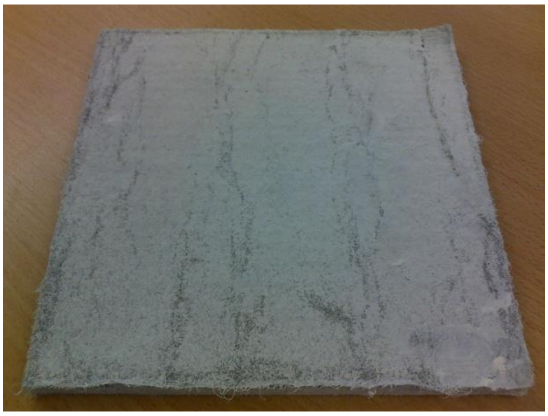

Figure 4. Unsatisfactory surface coverage.

The FP 1908 coating was suitable for spraying but the coating thickness was difficult to control which resulted in an unpredictable quality of the surface finish with many samples demonstrating an “orange peel” type of surface finish as shown in Figure 4. This was considered to be unacceptable and other processes were thus investigated.

b *Dipping*

A dipping process was seen as highly favourable as it allows for a single process to simultaneously coat all sides of the sample. This has great benefits from a time and cost perspective and trials were conducted to assess the viability of this process. The most promising samples were fully coated but once again the issue was with the control of the coating thickness.

c *Rolling*

The suitability of this application process to the FP 1908 coating material was found to resolve two of the issues identified previously; being a full even surface coverage and a consistent coating thickness. When the coating was rolled onto the surface of the aerogel, the open-cell foam of the roller spread the coating material out evenly across the surface of the aerogel allowing for a thin and even thickness of coating onto the aerogel surface. The contact between the roller and the aerogel caused the fibrous hairs on the surface of the aerogel to lay flat once the coating was applied, thus resolving the issue identified with other processes . This provided the correct quality surface finish that the product required as shown in Figure 5 and 6. This process was thus used for the manufacture of all impending former prototypes.

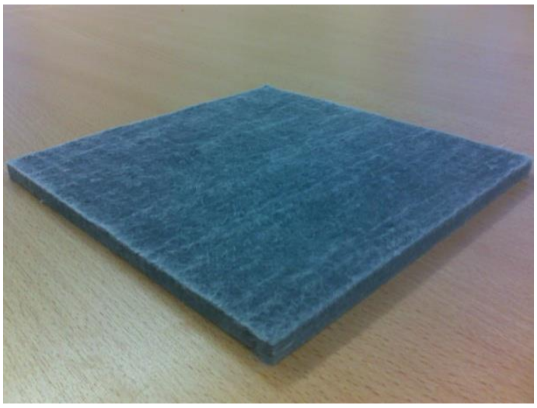

Figure 5. Pre-encapsulation aerogel sample.

Figure 6. Post-encapsulation aerogel sample.

5 SURFACE FINISH MATERIAL

An appropriate surface finish was researched. This involved an understanding of the regulatory requirements as well as research into the capabilities of products already available. The purpose of this approach was to identify a set of target properties which any surface finish would need to achieve as outlined below:

a. Thickness
b. Durability
c. Fire rating
d. Cost
e.

Table 2 below shows a shortlist of the materials that were deemed appropriate for further investigation. It was clear from a simple shortlist comparison that the magnesium-silicate board material was more suitable than the others. This material possessed all the necessary properties to provide a suitable surface finish with the main disadvantage being the significant increase in weight.

Table 2. Surface laminate properties

Material	cost (£ / sheet)	thickness (mm)	fire rating	weight (kg)
Thermoplastic PETG	5.00 – 8.00	1.00 – 1.50	Euroclass D	0.75
Magnesium-silicate	1.40	3.00	Euroclass A1	2.28
Woven polypropylene	1.88	0.30	Euroclass D	0.15
Thin plasterboard	2.50	6.00	Euroclass A2	3.96

Any significant increase in weight would have an impact on the adhesion between the finished product and the substrate. Also, the final design must be suitable for DIY installation. To achieve this requirement the use of adhesive fixing was deemed more appropriate over mechanical fixing; as these would require a higher degree of competency, thus restricting the products appeal.

6 CURRENT BUILDING REGULATORY REQUIREMENTS

The minimum current U-value for solid wall refurbishment is 0.7 W/m^2.K. This played an important role in the development of the new insulation product as it establishes the performance target to which the new product needs to comply as outlined in the UK Building Regulations, Approved Document L1B, in HM Government, (2010).

6.1 *Thermal conductivity testing*

Table 3 below shows the results from thermal conductivity tests which were carried out by the aerogel manufacturer. As can be seen, the pre-encapsulation control samples have a thermal conductivity of 18 miliwatts while the post-encapsulation results vary by 1.33 miliwatts. This is due to the FP 1908 encapsulation material having a greatly reduced solids' content as well as a significantly lower viscosity than the FP 1283 coating. These test results demonstrate that the FP 1908 encapsulation has the least effect on the thermal performance of the aerogel. Based on these results, the FP 1908 material was selected as the primary encapsulation coating.

Table 3. Thermal conductivity test results

Encapsulation type	application method	pre-encapsulation	Post-encapsulation	units
FP 1908	1 coat – rolled	18.00	20.00	mW/mK
FP 1283	1 coat – rolled	18.00	21.33	mW/mK

6.2 *U-value calculations*

U-value calculations for composite walls incorporating the aerogel product are shown in Table 4 below and were undertaken using the BRE U-value calculator version 2.03. Results suggest that the 18mm coated aerogel insulation product can meet the regulation requirements.

Table 4. U-value calculations for solid wall types

Wall Construction	Base Wall	13mm Wall Liner	18mm Wall Liner	Units
225mm Brick	2.06	0.86	0.67	W/m^{2}K
300mm Brick	1.72	0.78	0.63	W/m^{2}K
600mm Stone	2.18	0.87	0.68	W/m^{2}K
Brick cavity- Unfilled	1.45	0.72	0.59	W/m^{2}K
Brick cavity- Filled*	0.58	0.41	0.37	W/m^{2}K

All walls 13mm plaster on hard with 2mm air gap
*Brick cavity wall with insulation assumed at 0.038W/m^{2}K

It is intended that the final product will be adhesively bonded to the internal face of a solid wall. Therefore, for the intentions of these calculations, an internal surface finish of 13mm of plaster on hard was chosen as this will accurately represent expected on-site substrate conditions.

A recent SPAB report (2011) demonstrated that the actual differences between the thermal performance of upgraded traditional buildings and those calculated for the same buildings using Build Desk modelling software was overestimated in relation to the in-situ figure as demonstrated by Rye (2011). Based on this information, the U-value data shown in Table 4 above may also be overestimated; confirmation of this will be gained from future test trials.

7 ENCAPSULATION MVTR TEST RESULTS

The information in Table 5 below shows the vapour diffusion thickness for the two different versions of the same encapsulation material. In the bottom row it can be seen that test series 1908 has a diffusion thickness of 0.37 as opposed to test series 1283 which shows a vapour diffusion thickness of 0.65. Other than this variation and the difference in thermal conductivity shown in Table 3, there are no other significant differences between these two encapsulation variants.

Table 5. MVTR tests results

Material property	FP 1908 value	SD	FP 1283 value	SD	Units
Water vapor permeance	5.27E-10	7%	2.99E-10	5%	kg/s.m^2.Pa
Water vapor permeability	4.43E-12	5%	2.54E-12	7%	kg/s.m.Pa
Water vapor resistance	43.67	5%	76.41	7%	n/a
Vapor diffusion thickness	0.37	6%	0.65	5%	Sd value (m)

The thermal conductivity and MVTR test results show that the FP 1908 encapsulation material possessed the attributes necessary for successful encapsulation of the core aerogel material. Figure 7 and figure 8 below show the MVTR samples for both encapsulation materials.

Figure 7. FP1908 MVTR test samples.

Figure 8. FP1283 MVTR test samples.

8 CONCLUSION

This paper outlined issues with the core aerogel insulation material and methods of mitigating these have been highlighted through establishing the properties and limitations of the aerogel when used as a building material. Compression and tensile testing out of the product have demonstrated that the material exceeded the expected compression and tensile measurements by 10% to 15%. A product design suitable for adhesive bonding as opposed to the use of mechanical fixings was thus developed and demonstrated that the aerogel would not de-laminate under a significantly increased load such as those imposed by an encapsulation or additional surface laminate.

An appropriate encapsulation system using the FP1908 material was then developed in light of these findings. Important properties (thickness, durability, fire rating and vapour permeability) of the FP1908 encapsulation were satisfied without compromising any of the final product desired properties such as its thermal performance and fire rating. The minimal impact of the encapsulation on the thermal conductivity of the aerogel greatly assists in the availability of a more user-friendly high performance thin internal insulation product. The thickness of the final product shows that a maximum thermal performance can be gained for solid wall buildings with a minimal loss of internal room space, thus demonstrating its possible contribution to refurbishing hard-to-treat buildings and to the UK's climate change strategy.

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Appendix B-1:

Glasgow City Council - Stakeholder Meeting Minutes

Points discussed:

Specification

- The wall liner would be most suitable at a 10mm thickness.
- Don't consider acoustic properties to be particularly important.
- A board dimension of 2.4x1.2m is not suitable for accessibility, a smaller board is better (i.e.) 1.2x.6m.

Price

- An appropriate price point for the wall liner would be £20 to £25-(ideal) but £30 would also be acceptable.
- There is a need for Research on the labour involved in the wall liner application, as the less labour the better. The price could be increased if the labour was reduced.

Certification & Warranties

- Suggested warranty for the wall liner product of 25 years.
- BBA & OfGem approval should be sought for the new wall liner product.
- A product life expectancy of 60 years could be realistic.

Accessories & Additions

- There are approximately 70,000 pre 1919 tenement flats in Glasgow which are suitable for the wall liner product.

Appendix B-2

Historic Scotland, Edinburgh - Stakeholder Meeting Minutes

Points discussed:

Specification

- Could the wall liner could have a clay paint surface finish.
- The wall liner may incorporate oblique cuts at the edges to accommodate filler material.
- The possibility of using double sided tape as a method of adhesive fixing was also suggested (possibly silicone based).
- The use of a VCL is a non-issue and not relevant from their perspective.
- The wall liner should ideally have a hard outer surface finish and appropriate inner surface capable of receiving the adhesive.
- An Apply & Paint system would be a good option.
- The Spacetherm wall liner is not a phase change material and does not incorporate any PCM properties, although it was agreed that this should be looked at.
- A panel size of 1.2 x .6m or 1x1m would be fine.
- An important point is that the wall liner can be applied over an existing lining.
- Direct fixing or adhesive fixing would be suitable.
- In relation to the possible use of an adhesive double sided tape, 2 direct fixings could be used as a precaution.

Price

- A £50 price point would be considered appropriate.

Certification & Warranties

- Historic Scotland suggested that a warranty of 25 years would be ideal.
- A product life expectancy of 50 years plus would be good.
- If a product contains an additional benefit it may not be classed as a thermal refurbishment, properties such as acoustics, indoor air quality and thermal performance are good plus points.
- Historic Scotland said that the Building Reg's apply only when there is a warrant issued.

Accessories & Additions

- Radiant Wire systems may be a suitable future product in relation to a new insulation, humidity buffering and heating product.

- In relation to carrying out room surveys, is was suggested that a laser scanner can be used to accurately measure the room dimensions from which the number of panels could be calculated.
- Historic Scotland suggests that the wall liner could be divided into 2 types relating to returns on internal partitions, (1) Thermal and (2) Non-Thermal / Acoustic perhaps.
- There may be a possibility for 2 products (1) Vapour Permeable and (2) Non-Vapour Permeable.

Appendix B-3

Change Works, Edinburgh - Stakeholder Meeting Minutes

Points discussed:

Specification

- Change Works suggested that having the option of a wall liner with and without a VCL is interesting and the choice would be favourable.
- Change Works feel the need to have a removable product is not important in their view as opposed to Historic Scotland.
- If a building is not historically important then the use of an adhesive should be fine. Otherwise it may need to be removable.
- The product needs to be easily installed, so the less disruption the better.
- People will compromise on the U-value just to have a thin wall liner.
- The slim system has great benefits and would be worth the cost.
- In relation to price, it was pointed out that the cost of blown bead insulation differs as much as £15 to £150m^2.
- It was suggested that the Solid Wall report carried out by Change Works be reviewed.
- Consideration needs to be given to people in rural areas in terms of making the product accessible as the rural market would be more DIY oriented therefore local contractors will be useful.
- DECC are going to use set reduction factors for loft and wall insulation (25% for wall insulation).

Price

- Change Works has suggested that a price point of about £40 to £50m^2 would be reasonable, they feel that £50/m^2 might be expensive but there may be no way around it.

Certification & Warranties

- A warranty of 25 years will be appropriate.
- The product life expectancy should be as long as possible or at least 40 years.

Accessories & Additions

- In relation to size, the size is not as important as the other issues but the larger the better.
- A level of flexibility would be desirable.

Appendix B-4

Scottish & Southern Energy - Stakeholder Meeting Minutes

Points discussed:

Specification

- As a funding provider, SSE would have concerns about a new products compatibility with proposed Government initiatives.
- The wall liner could be highly suited to use in internal partition returns.
- Much greater clarity is needed on the definition of what a hard to treat home actually is.
- If the wall liner is used in conjunction with internal cavity insulation it could work very well as a hybrid system.
- However if the wall liner was used with an external wall system it could work out very expensive on the costumer.
- Will the wall liner price point be competitive with other currently available systems?
- The wall liner will be competitive in niche markets.
- It is important to identify building types in specific areas that are suitable as trial sites for the wall liner.
- If a U-value of 0.3 or 0.5 W/m^2k is to be achieved the cost involved will be significant.

Price

- A competitive price would be desirable.

Certification & Warranties

- The warranty of the product should also match the life of any Government funding initiative.

Accessories & Additions

- SSE did not suggest any accessories or possible additions but agreed with that the wall liner could be very good for partition returns and also for use in hybrid systems.

Appendix C:

Spacetherm F10								
dwelling	no.beds	M2 req	Material cost	Funding	Installation	KWH saving/y	£ savings/y	**Payback in years**
Flat	1	26	£1,170	£0	£260	2,833	£198.33	**7.2**
Flat	2	32	£1,440	£0	£320	3,415	£239.02	**7.4**
Flat	3	38	£1,710	£0	£380	4,124	£288.71	**7.2**
Mid-Terrace	2	43	£1,935	£0	£430	3,514	£245.97	**9.6**
Mid-Terrace	3	48	£2,160	£0	£480	3,935	£275.44	**9.6**
End-Terrace	2	76	£3,420	£0	£760	6,644	£465.07	**9.0**
End-Terrace	3	84	£3,780	£0	£840	7,440	£520.79	**8.9**
Semi-bungalow	2	58	£2,610	£0	£580	5,052	£353.65	**9.0**
Semi-bungalow	3	63	£2,835	£0	£630	5,454	£381.77	**9.1**
Det-bungalow	2	72	£3,240	£0	£720	6,123	£428.60	**9.2**
Det-bungalow	3	77	£3,465	£0	£770	6,606	£462.45	**9.2**
Det-bungalow	4	83	£3,735	£0	£830	7,096	£496.75	**9.2**
Semi-house	2	83	£3,735	£0	£830	7,259	£508.11	**9.0**
Semi-house	3	90	£4,050	£0	£900	7,804	£546.27	**9.1**
Semi-house	4	96	£4,320	£0	£960	8,354	£584.80	**9.0**
Det-house	2	130	£5,850	£0	£1,300	11,435	£800.43	**8.9**
Det-house	3	140	£6,300	£0	£1,400	12,292	£860.43	**8.9**
Det-house	4	150	£6,750	£0	£1,500	13,204	£924.25	**8.9**
		all values include the 15% comfort factor reduction						

Payback Calculations Table (*Based on 2012 Data*)