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The Green Nanothermal Insulators in Architecture and Construction

Amin Saboktakin[1], Mohammadreza Saboktakin[2]

[1]*Architecturedepartment, Hochschule Wismar, Germany*
[2]*Nanotechnology department, Phillips University of Marburg, Germany*

***Corresponding Author:** Amin Saboktakin, Architecturedepartment, Hochschule Wismar, Germany*

ABSTRACT

Thermal insulators in buildings is an important factor to achieving thermal comfort for its occupants. Insulation reduces unwanted heat loss or gain and can decrease the energy demands of heating and cooling systems. It does not necessarily deal with issues of adequate ventilation and may or may not affect the level of sound insulators. In a narrow sense insulation can just refer to the insulation materials employed to slow heat loss, such as: cellulose, glass wool, rock wool, polystyrene, urethane foam, vermiculite, perlite, wood fiber, plant fiber (cannabis, flax, cotton, cork, etc.), recycled cotton denim, plant straw, animal fiber (sheep's wool), cement, and earth or soil, Reflective Insulation (also known as Radiant Barrier) but it can also involve a range of designs and techniques to address the main modes of heat transfer - conduction, radiation and convection materials. Many of the materials in this list deal with heat conduction and convection by the simple expedient of trapping large amounts of air (or other gas) in a way that results in a material that employs the low thermal conductivity of small pockets of gas, rather than the much higher conductivity of typical solids. (A similar gas-trapping principle is used in animal hair, down feathers, and in air-containing insulating fabrics).

INTRODUCTION

Nanotechnology, shortened to "nanotech", is *the study of the control of matter on an atomic and molecular scale*. Generally nanotechnology deals with structures of the size 100 nanometers or smaller in at least one dimension, and involves developing materials or devices within that size. Nanotechnology and nanoscience got started in the early 1980s with two major developments:

- the birth of cluster science
- the invention of the scanning tunneling microscope (STM)

This development led to the discovery of fullerenes in 1985 and carbon nanotubes a few years later. Nanotechnology Can Make A Concrete Contribution To The Following Areas:

- Optimization of existing products.
- Damage protection.
- Reduction in weight and / or volume.
- Reduction in the number of production stages.
- A more efficient use of materials.
- Reduced need for maintenance (easy to clean, longer cleaning intervals) and / or operational upkeep. And as a direct result:
- Reduction in the consumption of raw materials and energy and reduced CO_2 emissions that will affect good in environment.
- Conservation of resources.
- Greater economy.
- Comfort.

Dozens of building materials incorporate nanotechnology, from self-cleaning windows to flexible solar panels to Wi-Fi blocking paint, and many more are in development, including self-healing concrete, materials to block ultraviolet and infrared radiation, smog-eating coatings and light-emitting walls and ceilings. Example are:

- Carbon fiber
- Energy coating
- Heat absorbing windows
- Nano coatings
- INSULADD,®QuantumSpheres,andNano aluminium powders.

- Ultra Low Energy High Brightness Light (ULEHB).
- Nano sensors.

Lighting will produce the same quality light as the best 100 watt light bulb (Sustainable Energy), but using only a fraction of the energy and last many times longer. These new ultra low energy lighting devices will be fabricated using carbon nanotube organic composites which will significantly reduce energy running costs, thus reducing carbon dioxide emissions at power generating stations Potential uses such as variable mood lighting *over a whole wall or ceiling* opens up a range of exciting applications. ULEHB is also expected to have wide uses in signage, displays, street lighting, commercial lighting, public buildings and offices. Nano sensors can monitor temperature, humidity, and airborne toxins, vibration, decay and other performance concerns in building components, from structural members to appliances. The *Nano Vent-Skin* is a zero-emission material that takes a tri-partite approach (*sunlight,wind,*CO_2) towards energy efficiency.

- The outer skin of the structure absorbs sunlight through an organic photovoltaic skin and transfers it to the nano-fibers inside the nano-wires which then is sent to storage units at the end of each panel.
- Each turbine on the panel *generates en*ergy by chemical reactions on each end where it makes contact with the structure. *Bioengineered organisms* are responsible for this process on every turbine's turn.
- The inner skin of each turbine, made of bioengineered organism, works as a filter absorbing CO_2 from the environment as wind passes through it.

In architecture there are two different design approaches for materials and surfaces:

- Honesty of Materials – "what you see is what you get"
- Authenticity is a priority; high-quality materials such as natural stone or solid woods.
- Fakes/artificial surfaces that imitate natural materials For the most part, fake materials are chosen for cost reasons. Artificial surfaces are brought to perfection; the *grain* can be tailored to appear exactly as desired; the *color* matches the sample precisely and does not change over the course of time. Certain design approaches prefer the provocation of *deliberate artificiality.*
- In future, a third option will be available:
- Functional Nanosurfaces, emancipated from underlying materials

The properties of such ultra-thin surfaces can differ entirely from the material they enclose and can be *transparent* and *completely invisible*. Also possible are nanocomposites with new properties:

- Nanoparticles or other Nanomaterials are integrated into conventional materials so that *the characteristics of the original material are not only improved but can be accorded new functional properties or even be made multifunctional*.
- Surface materials that are customized to have specific functional properties are set to become the norm, *switching from catalogue materials to made-to-measure materials* with definable combination of properties – a perfectly modular system.

Materials reduced to the nanoscale can show very different properties compared to what they exhibit on a macroscale:

- Opaque substances become transparent (*copper*)
- Inert materials attain catalytic properties (*platinum*)
- Stable materials turn combustible (*aluminum*)
- Solids turn into liquids at room temperature (*gold*)
- Insulators become conductors (*silicon*)

One-Dimension: Thin Films, Layers and Surfaces

One-dimensional Nanomaterials have been developed and used for decades in fields such as electronic device manufacture, chemistry and engineering Thin Solar film Two-dimension: tubes and wires.

- *Carbon nanotubes* (CNTs) are extended tubes of rolled graphene sheets. They are mechanically very strong, flexible (about their axis), and can conduct electricity extremely well. CNTs are used in in reinforced composites, sensors, nanoelectronics and display devices.

- *Nanowires* are ultrafine wires or linear arrays of dots, formed by self-assembly. Nanowires demonstrated remarkable optical, electronic and magnetic characteristics and have potential applications in highdensity data storage

Three-Dimension: Nanoparticle and Fullerens

- *Nanoparticles* are often defined as particles of less than 100nm in diameter. They exhibit new properties (such as chemical reactivity and optical behavior) that compared with larger particles of the same materials. Titanium dioxide and zinc oxide become transparent at the nanoscale, however are able to absorb and reflect UV light, and have found application in sunscreens. For most applications, nanoparticles will be fixed, for example attached to a surface or within in a composite.
- *C60 (buckminsterfullerene*) are spherical molecules about 1nm in diameter, comprising 60 carbon atoms arranged as 20 hexagons and 12 pentagons: the configuration of a football.
- Bacteria are targeted and destroyed.
- The use of disinfectants can be reduced.
- Supports hygiene methods - Especially in health care environments.

With the help of silver nanoparticles it is possible to manufacture surfaces specifically designed to be antibacterial or germicidal. Whether in the form of ultra-thin and invisible coatings or materials to which the particles have been added, these have an effect stronger than antibiotics. The antibacterial effect of silver results from the ongoing slow diffusion of silver ions. The very high surface area to volume ratio of the nanoparticles means that the ions can be emitted more easily and therefore kill bacteria more effectively. Bacteria have no chance of survival as the ions firstly hinder the process of cell division, secondly destabilise the cell membrane, walls or plasma and thirdly interrupt the enzyme's transport of nutrients. In this way, bacteria can be lastingly eradicated without the use of chemicals. The antibacterial effect itself is also permanent - it does not wear off after a period of time. Silver nanoparticles of on average 10-15 nm in size lend the paint antimicrobial properties that remove the basis for mould and mildew. The particles are chemically stable and firmly anchored in the paint. The antimicrobial agent therefore cannot be washed out and the antibacterial function remains intact for many years. Three years later, no mould infestation is to be seen. The use of nanotechnology in this case offers an environmentally friendly and effective solution without the need for strong chemicals, and prevents further damage to the elevations The floors and walls have been clad in photocatalytic tiles. Large format tiling is more difficult to lay, and a conventional tile format was chosen for the high-tech antibacterial tiles used in the Harzkliniken. The light-colored grouting contrasts pleasantly with the fresh green tiling Pleasant upholstered fabrics are used and still remain clean due to the antibacterial and dirt-resistant properties of nano silver particles. Light switches or floor surfaces, which are both subject to greater exposure to germs, are treated similarly. Quality wood veneers can be used thanks to antibacterial varnishes.

The historical precursor to vacuum insulators is the thermos flask: *low thermal conductivity is achieved by evacuating the air entirely* and the cylindrical form withstands the high pressure created by the vacuum. This approach is more difficult for flat insulation layers as they are unable to withstand the pressure. The solution to the problem is the use of an extremely fine fill material with a nanoscalar porosity of around 100 nm. A comparatively low pressure is then sufficient to evacuate the air making it possible to construct panels that can be used in building construction. The thickness of these VIPs ranges from 2 mm to 40 mm. The panels are constructed as follows: an *enveloping skin made of plastic foil (often coated with aluminium) or of stainless steel encloses the fill material in a vacuum*. The fill material takes the form of a *foam, powder or glass fibers and is always porous, resists pressure and can be evacuated*. The hermetically weld-sealed ends protrude on each side and are usually folded back and stuck to the panel. For the panels to function correctly, it is imperative that the vacuum-enclosing skin is not pierced. Careful planning is necessary in order not to impair the insulating effect of the VIPs. *Gaps between neighboring panels must be minimized* as far as possible to avoid cold bridges (heat leaks) resulting when the gap is too large. VIPs are *more expensive than conventional insulation materials* and today are not necessarily conceived as a general replacement for conventional insulation. The lifetime of modern panels is generally estimated at *between 30 and 50 years.* Aerogel currently holds the record as the lightest known solid material and was developed back in 1931. The gel is a globular granulate and appears milky, translucent and somewhat cloudy. It is simply an *ultra-light aerated foam* that consists almost 100% of nothing other than air (the exact figure varies between 95% and 99.9%). The remaining foam material is a *glasslike material, silicon dioxide, also known as silica*. The nanodimension is of vital importance for the pore interstices of the foam: the air molecules trapped within the minute nanopores - each with a mean size of just 20 nm - are unable to move, lending the aerogel its excellent thermal insulation properties. In addition to its thermal insulating properties, aerogel also acts as a sound insulator according to the same basic principle. Because it is translucent, aerogel exhibits good light transmission, spreading light evenly and pleasantly.PCMs are invariably made from paraffin and salt hydrates. Minute paraffin globules with a diameter of between 2 and 20 nm are enclosed in a sealed plastic sheathing. These can be integrated into typical building materials (plasters, plasterboards or aerated concrete blocks), whereby around 3 million such capsules fit in a single square centimeter. An image of minute paraffin-filled capsules in their solid state, taken using light microscopy. They exhibit an exceptionally high thermal capacity and during a phase change turn to liquid. During a phase change, the warmth is retained latently for as long as is required to change from one physical state to another. As PCM is able to take up energy (heat) without the medium itself getting warm, it can absorb extremes in temperature, allowing indoor areas to remain cooler for longer, with the heat being retained in the PCM and used to liquefy the paraffin. As the temperature rises, melting the waxy contents of the microcapsule, the paraffin changes from solid to liquid. The same principle also functions in the other direction: rooms that are cooling down stay warm for longer, while the molten paraffin gradually hardens, before losing warmth. The temperature level of the materials remains constant.The predefined temperature is defined as 25°C. The central of three cavities of an *8 cm thick composite glass* element contains a salt hydrate fill material that functions as a latent heat store for solar heat and protects the rooms from overheating. The latent heat store has a *thermal absorption capacity equivalent to a 15 cm thick concrete wall*. The glass panel is *transparent when the fill material has melted and milky-white when frozen*. To function adequately, the air-purifying surface area must be sufficient with regard to the volume of the room. Only surfaces that are exposed to the air, i.e. those not concealed by furniture, are relevant. For processes based on oxidative catalysis, normal air circulation is sufficient. Nicotine or formaldehyde molecules can also be cracked and filtered out of the indoor air. The air-purifying capacity of photocatalytic concrete for example provides a possible means of combating existing pollutants. Applications are air-purifying paving stones, road surfaces and paints. Depending on the respective conditions, it was possible to eradicate between 20% and 80% of airborne pollutants. Pedestrians walking in the vicinity of treated walls breathed in fewer airborne pollutants. The advent of nanotechnology has provided a new means of integrating electrochromatic glass in buildings. The primary difference to the earlier product is that a constant electric current is no longer necessary. A single switch is all that is required to change the degree of light transmission from one state to another (from transparent to darkened). Photochromatic glass is another solution for darkening glass panels. Here the sunlight itself causes the glass to darken automatically without any switching. A thickness of only 3 mm of a functional fill material between glass panes is sufficient to provide more than 120 minutes of fire resistance against constant exposure to flames of a temperature of over 1000°C. The pyrogenic silicic nano particles, or nano-silica, are only 7 nm large and due to their relatively large surface area highly reactive. Depending on the desired duration of fire-resistance, the highly effective fill material is sandwiched between one or more panes of glass. The size of the fill particles can be modified and is given in terms of its surface area in square meters per gram. In the event of a fire the nanosilicate forms an opaque protective layer against the fire, which also protects against heat radiation. They are highly effective and are used to make building materials water-repellent. Their extremely hydrophobic properties mean that graffiti can be removed more easily with appropriate detergents. Even porous and highly absorbent materials such as brick, lime sandstone, concrete and other similar materials can be protected efficiently using such nano-based coatings. Although the coating is effectively an impregnation, unlike other systems it does not close the pores of the material, allowing the material to retain its vapourpermeability.The ultra-thin nanocoating lines the capillary pores without closing them. In addition, the coating also reduces dirt accumulation significantly, making the coating applicable for use on floor surfaces too. The effect of the impregnated coating is a result of several layers of molecules. Within the coating, the self-organization of the molecules it contains ensures that these are distributed evenly, stay together and have the same orientation. The upper layer fulfills a hydrophobic function, with a significantly reduced surface tension and molecular attraction. The lower layer ensures the entire coating adheres to the substrate it is applied to. Both buildings have exposed concrete facades whose clean-cut forms are best appreciated when the surfaces are equally clean. For this reason the concrete surfaces have been coated with a nanoscale high-tech coating. Such dirt-repellent anti-graffiti surfaces are well suited for use in urban environments where the potential for undesirable defilement is particularly great. Unsightly damage to buildings can be avoided as a result. Its central location attracts graffiti-sprayers and it is only a matter of time before the first graffiti will appear on walls outdoors. An anti-graffiti coating was applied to guard against such damage, which protects the surface without clogging the capillary pores. The material itself is still permeable and able to breath. Pink stays pink. Transparent nanoscale surface structures, where the particles are smaller than the wavelength of visible light, offer not only an innovative but also a cost-effective and efficient anti-reflective solution. Their structure consists of minute 30-50nm large silicon-dioxide ($SiO2$) balls. A single interference layer is applied by dipping the glass or plastic in the solution and functions across a broadband spectrum of light. The refractive index of the outer layer is very small and can be defined precisely, as can the thickness of the coating. A thickness of *150nm* is regarded as ideal. *The ratio of reflected light reduces from 8% to less than 1%.* Steel and satin-finish glass surfaces are particularly affected by repeated touching. The coating alters the refraction of the light in the same way the fingerprint itself does so that new fingerprints have little effect. The light reflections on the coating make steel or glass surfaces appear smooth, giving the impression of cleanliness that many users have come to expect. NANOTECHNOLOGY, a science that works on the molecular scale is set to transform the way we build. Nanotechnology, the design and fabrication at the molecular scale, is opening new possibilities in green building through products like solar energy collecting paints, nanogel, high-insulating translucent panels, and heat-absorbing windows. Even more dramatic breakthroughs are now in development such as paint-on lasers that could one day allow materials to send information to each other, windows that shift from transparent to opaque with the flip of a switch, and environmentally friendly biocides for preserving wood. Ubiquitous sending is likely to bring a host of benefits including customized temperature settings in buildings, light-sensitive photochromic windows, and user-aware appliances. These breakthrough materials are opening new frontiers in green building, offering unprecedented performance in energy efficiency, durability, economy and sustainability. The nanotechnology application for green building have an emphasis on the energy conservation capabilities of architectural nanomaterials and the role of nanosensors in green building:

Nanotechnology revolution is bringing dramatic improvements in building performance, energy efficiency, environmental sensing, and sustainability, leading the way to greener buildings. The nanotech and building sector have to yet to get to know each other a lot better in order to realize the dramatic benefits awaiting each of them. The nanotech community needs to be explored and explained the enormous economic opportunities in Green Building Design, Construction and Operation; and demonstrate to Architects, Building Owners, Contractors, Engineers and others in the $1 trillion per year global building industry that nanotech is at this moment beginning to fulfill its promise of healthful benefits for people and the environment. According to the 2009 Green Building Market & Impact Report, the green building sector has maintained constant growth throughout 2009 despite a coarse year for the construction market. And, many cities have adopted stringent green building requirements for new construction, and developers must find new ways to meet them. It is predicted that nanotech's many environmental performance benefits will be led by current improvements in solar insulation and coatings, followed by advances in water and air infiltration, solar technology and, more distant, in lighting and structural components. As an example, we can point to available improvements in nanocoatings for insulating, self-cleaning, UV protection, corrosion resistance and waterproofing. Some available coatings are considered "healers", in that they remove and render benign pollutants from a building'ssurrounding atmosphere.

While there are the obstacles to widespread adoption of nanotech in the building industry, there are news of the many nano-enhanced products currently on the market that have been demonstrated to outperform conventional products.We can take advantage of some of the many uses of nanotechnologies,, from solar energies to structural materials to insulation, help make green buildingsmore cost-effective, more energy-efficient and more in tune with their environments. With one in three new US construction projects registered for LEED certification, there's a bigger need for new green building technologies. One such next-generation technology is nanotechnology, and it's utilizing new materials that defy conventional thinking. Spray-on Solar cells, volatile organic compounds VOC-eating Nanocoatings, and windows that change color at the flip of a switch; they are here today and they promise to change the future of Green Building.We will need to learn to identify nanotechnology products that meet our specific green building needs, compare their costs and benefits, and evaluate their environmental, health and safety impacts. Nanotechnology, the understanding and control of matter at a scale of one to one hundred-billionths of a meter, is bringing incredible changes to the materials and processes of building. How ready we are to embrace them could make a bigdifference in the future of architectural practice and construction. Already, this new science of the small has brought to market self-cleaning windows, smog-eating concrete, and toxin-sniffing nanosensors.But these off-the-shelf advances offer only a taste of what's incubating in the world's nanotech labs today. There, work is underway on nanocomposites thin as glass, yet capable of supporting entire buildings, andphotosynthetic coatings that can make building surface a source of free energy. Nanotechnology works by tweaking matter from the bottom up. Recent advances in scanning electron microscopes and other technologies now make it possible to see and manipulate matter at the molecular scale more economically than ever before. Using these tools, nanoscientists are creating revolutionary materials like coatings a single atom thick, carbon nanotubes up to 50 times stronger than steel yet 10 times lighter, and quantum dots that could enable us to change the color of almost any object instantaneously.These remarkable effects are achievable because matter behaves differently at the nano-scale, where the laws of quantum physics take hold. In this quantum world, objects can change color, shape, and phase much more easily that at the macro scale. Fundamental properties like strength, surface-to-mass ratio, conductivity, and elasticity can be engineered to create dramatically different materials. The building products currently using nanotechnology and look ahead at the Next Generation Green Building technologies:

I. We live in an age where scientific progress continues to transform human lifestyle. This is even more true when it comes to the progress being made in the field of nanotechnology. This science stands to change and advance the practice of design in a multitude of ways – where architectural progress is being made at the molecular level. A design area that will be influenced by nanotechnology is the smart environment. Here, tiny embedded nano sensors will make architectural features responsive. Communication will occur between object and object, between occupant and object, between object and environment and between occupant and environment. As new materials gain more transient properties, objects and architectural features will impact the process of design by making 'fields of interaction' a major focus.By working on 'fields of interaction' architecture professionals will have some framework by which to design for dynamic environments. Since smart architecture will be changing states and communicating heavily, architects will likely focus on relationships as much as they focus on design forms during the design stage. It is likely that both forms and their relationships will make up rule-based systems by which smart architectural spaces can function. Nanotech's 'wonder materials' have the potential to revolutionize how and what we build. One day, carbon nanotubes and other nanomaterialscould so radically transform our material palette that paper-thin sheets might hold up entire building, forcing us to completely rethink the relationship between structure and skin. Carbon nanotubes, sheets of graphite just one atom thick, formed into a cylinder, are not only 50 times stronger than steel and 10 times lighter, they are transparent and electrically conductive to boot. Nanotubes are already the building blocks for hundreds of applications, used to reinforce concrete and deliver medication to individual cells. Nano composites, which combine new nano materials with more traditional ones such as steel, concrete, glass and plastics, can be many times stronger than standard materials. Already on the market is a nano composite steel that is three times stronger than conventional steel. In the near term, nano composite reinforcement of steel, concrete, glass, and plastics will dramatically improve the performance, durability, and strength-to weight ratio of these materials. Before long, nano-reinforced glass might be used for both structure and enclosure.As threats from terrorism and even from natural forces like hurricanes rise, we will utilize the strength of nano tubes to make our buildings more secure.Research that is now underway to make Army vehicle windshields bomb-proof, using polycarbonate reinforced nano fibers, may soon be applicable tobuilding glass. Nano coatings nano materials stand to revolutionize insulating methods because they are structured at the molecular level to trap air between particles. They are far more efficient than traditional insulators like fiberglass and polystyrene which work at the macro level, without the environmental harm associated with those materials. And because it traps air at the molecular level, an insulating nanocoating even a few thousandths of an inch thick can have a dramatic effect. Nanogel insulation, made by the Cabot Corp, is a form of aerogel, the lightest-weight solid known as 'frozen smoke' nanogel is 5% solid and 95% air The high air smoke , air. content means that a translucent panel 3.5 inches thick can offer a high insulating value. Another company, Nanoseal, makes insulating paint for buildings. Its insulating coating, applied in a layeronly seven-thousands of an inch thick, is being used on beer tanks in Mexico by Corona, resulting in a temperature differential of 36 degrees Fehrenheit. Nanocoatings are used to insulate both new and existing materials, and to protect wood, metal, and masonry, without the hazardous off-gassing of many other coatings. Nanoengineered ultraviolet curable protective coatings by Ecology Coatings won 2006's Silver Award for Innovation in The Wall Street Journal's Technology Innovation Awards competition. Garbage, paper, and other renewable can be formed into products, but they have a tendency to dissolve in water. A very light coating of the nanocoating product can be used to waterproof these, and they can be used as a substitute for plastic. Nanocoatings can be used to self-clean surfaces, and in the process they de-pollute; they actually remove air pollutants and dissolve them into relatively benign elements. De-polluting nanocoatings break down toxins that come in contact with surfaces. When painted onto a road, bridge or building they not only protect the surface and reduce the need for cleaning – they eliminate some of the pollution that cars emit. It's invisible and non-toxic. Self-cleaning windows were one of the first architectural applications of nanotech. The coating causes water to sheet off the surface, leaving a clean exterior with minimal spotting or streaking. Nanotec's coatings are on many buildings around the world now. Its nano treatments self-clean concrete and stone, glass and ceramics, textiles, wood, stainless steel, aluminum, and plastic. A building stays clean much longer, especially the windows, reducing the need for toxic chemical cleaners which emit volatile organic compounds VOCs. Kohler and other plumbing fixture manufacturers are starting to paint anti-microbial coatings on sinks and toilets, which means less maintenance and lower costs**.** Microban International manufactures an anti-bacterial chemical compounds for incorporation into molecular plastics and synthetic fibers, imparting resistance to the growth of bacteria, molds and mildew that can cause stains, odors and deterioration of a product. Built into products during the manufacturing process, its antimicrobial product protection is used in over 450 products including cleaning supplies, paints, caulking and plumbing fixtures, provide an added level of defense against damaging microbes for the useful lifetime of the product. In the future, the technology could make pipes so smooth and slippery that they can't plug up, wear out, and can carry much more water in a smaller pipe. Nanotech Solar is starting to offer real competition to conventional silicon-based solar manufacturing. It isn't as efficient as conventional solar, but is steadily improving. It could replace silicon technology in 3-7 years. The Department of Energy estimates that nearly 50% of the electrical needs of buildings in the US can be met by BIPV systems. NanoSolar has received investments from some of the venture capital powerhouses, along with individual investors like the founders of Google. The company has the potential to transform the solar market with its 'roll to roll' process, where thin film, nanotech solar cells are literally printed onto plastic or metal. It makes integrating solar into a building more like printing a newspaper, a major advance from glass plates that are installed on rooftops. Solar sheets can be made for less than a tenth of what current panels cost at a rate of several hundred feet per minute. Its SolarPly BIPV panels, made from semiconductor quantum dots and other nanoparticles, will create solar-electric "carpet" to be integrated into commercial roofing membranes. Spire Corp integrates solar into façade elements like windows and awnings. Its nanostructured materials make fabricating solar cells more efficient and enables solar to be available in various colors, giving architects options for improved aesthetics. Innova-light is developing silicon ink-based printed solar cells. By processing silicon with liquids, the company believes it can reduce the cost of solar by substantial percentage. Carbon Nanotubes are said to be one hundred times stronger than steel because of its 'molecular perfection'. In addition, because carbon atoms can bond with other matter; such materials can be an 'insulator, semi-conductor or conductor of electricity'. As a result, carbon nanotubes will have significant influence on the architecture industry as such materials can act as a 'a switchable conduit, a light source, a generator of energy and even a conveyor of matter'. The building sector is accountable for a significant part of global energy consumption, greenhouse gas (GHG) emissions and waste generation. The United Nations Intergovernmental Panel on Climate Change (IPCC) is reporting that close to a quarter of the global total energy-related carbon dioxide (CO_2) emissions are stemming from the building sector [3]. Much attention is therefore focused on energy efficiency and emission abatements in this sector. As a part of this, the Research Centre on Zero Emission Buildings (ZEB) is developing buildings with zero net GHG balance throughout the life cycle. The buildings life cycle include raw material extraction and processing of construction materials, building construction, operative life and finally demolition and construction waste managent. Addressing energy demand for heating and cooling is assumed to have the largest and most cost-effective energy and GHG reduction potential in buildings [2, 4]. This has lead to a growing demand of increasingly thicker insulation. However, this comes at the expense of floor space, which is a problem from architectonic and economic perspectives. Also, thick walls steal daylight from windows. In addition, material requirements and transport volumes increase, which again affect the total amount of GHGs emitted. By nanostructure manipulation, new materials can be fabricated with very good insulating properties. Nanotechnology insulation material (NIM) can therefore be applied in considerable smaller thicknesses than conventional insulation materials. Application of NIMs to limit the wall thickness, while still achieving a satisfactory thermal resistance, is an important strategy on the pathway to sustainable buildings [5]. However, high-tech materials can be energy intensive and chemically demanding to produce, so it is important to avoid problem-shifting in the building's life cycle. Energy consumption in the operation phase of the building's life cycle traditionally dominates total life-cycle energy consumption. However, recent studies show that, in state-of-the art low energy buildings, the embodied energy of the construction risks to balance the operation energy because of the extended use of active components and advanced materials [6]. ZEB is developing a tool to calculate the contribution from the building materials to the environmental impact of the building [7] . In order for the tool to be useful, transparent environmental data of the different materials must be accessible. Currently, the availability of such data is low. ZEB is therefore interested in taking in the environmental perspective when developing a new nano insulation material based on hollow silica nanospheres (HSN). This new material is the object of study in this master thesis.The new nano insulation material is founded on the principle of confining air in extremely small pores within the structure. This is in order to lower the overall thermal conductivity of the material through, inter alia, the Knudsen effect. The idea of the hollow silica nanosphere type NIM is to try to create a super-insulating nanoporous material bottom-up from the spheres [8]. The intention is to make a high performance insulation material with interesting properties compared to conventional insulation. However, the product is at an early stage of development. The spheres are currently being produced with an average output in the order of 1 gram per synthesis. More research is needed on the final form of the material, e.g. how to make use of the spheres to create a building element with the desired properties. The production of the spheres are optimized for a successful lab experiment, and not yet optimized for a successful product. The material understudy is far from being optimized and may change considerably. This was the greatest challenge in this work: Trying to draw conclusions from a material of which almost all parameters still are variables. What properties must the material have in order to be an interesting investment? What form should the product take in order to be a useful, practical and robust building element? One requirement is that the insulation performance is good enough to off-set the economic investment costs due to room space saving. Other requirements include robustness, flexibility and safety with regard to nanoparticle issues, fire and moisture. Finally, the energy and GHG intensity of the material should not be too high, in order to compete with other technologies in the zero emission setting. At present, most of these challenges remain unanswered within ZEB. The goal of this work is not to answer all these questions, but to make advancement in the following two areas: The estimation of the effective thermal conductivity of the NIM and the environmental impact of its production. These two areas areconnected: Higher environmental costs can be tolerated per unit material thickness, if the thickness can be kept small. This is applicable whether the economic or ecologic investments costs are considered. Environmental system analysis is needed to quantify the environmental costs of the material. Life cycle assessment (LCA) is becoming an important tool for improving the environmental performance of materials, technology and construction in the building sector. LCA is a data-intensive tool in which the accuracy of the results depends primarily on the accuracy of the data input. The accuracy is problematic in cases like the one presented here, where the material is not yet finalized. However, the LCA method is well suited to search for and detect the most important environmental loads in the supply chain of a product, as to provide understanding on how the environmental performance can be improved. Hence, there are reasons to argue for LCAs to be performed at the earliest stage possible in the product development. Even if data accuracy is low at this stage, the LCA should be performed earlier rather than later, when the process is set and it is too late for improvements. A screening-LCA of the NIM is therefore useful in order to optimize the material design.The product assessed in this thesis is a nano insulation material (NIM). It will be referred to as the NIM, or as the silica nanosphere material, as it is based on hollow, nanoscopic spheres of silica (SiO_2). In brief, this is a new high performance insulating material founded on the principle of confining air in extremely small pores. This is in order to lower the overall thermal conductivity of the material through, inter alia, the Knudsen effect [9]. The NIM could be the new member of the family of state-of-the art insulation materials that have emerged the recent years. Among the most promising are aerogels and vacuum insulation panels (VIP). These materials will very briefly be presented here. More information can be found in, for instance, Jelle et al. 2010 [9].

Aerogel insulatorsis based on sol-gel technology of silica. The fluid in the silica gel is replaced by a gas in order to fabricate a solid material with a cross-linked internal structure of SiO_2-chains with a large number of nanoscopic pores filled with air (up to 99.8% air) [10]. Aerogels have very low densities and thermal conductivities. Aerogels have a wide range of applications. Its applications as insulation material is widely studied, see for instance Schultz et al. [11], Hostler et al. 2008 or Baetens et al. 2011 [5]. Aerogel insulation was also studied in the candidate's project thesis [2]. Commercial available areogel insulation are mostly made up of granular aerogel in fiber composites and have been reported to have thermal conductivities down to 0.013 W/mK [9]. However, aerogel insulation is expensive compared to conventional insulation materials.No environmental product declarations1 or life cycle assessments have been reported for commercial aerogel insulation products. One of the main producers, Aspen aerogels, are reporting some environtmental data, but will not share any of the calculation methods behind the numbers [2, 12]. A publication from Dowson et al. 2011 reports conservative estimates for the environmental impact of one cubic meter of aerogel based on laboratory experiments [13]. These results are not adapted for application in comparative analysis because of the non-compliance in the functional unit and boundary conditions.

Vacuum Insulation Panels (VIP) are achieved by applying a vacuum to an encapsulated micro-porous material [10]. VIPs represent state-of-the-art insulation with very low thermal conductivity, but it is associated with a degradation over time [14]. The thermal conductivities range from 0.003 to 0.004 W/mK in fresh conditions to typically 0.008 W/mK after 25 years aging, due to water vapor and air diffusion into the core. Puncturing the VIP

envelope causes an increase to about 0.02W/mK. The time-dependent degradation is a serious drawback, and more research is needed before a commercial break-through of VIP [8]. A comprehensive LCA report for two types of vacuum insulation panels were published by Schönhardt et al. 2003 [15]. Industry data from this report were obtained through AgnetaGhose who wrote a comparative LCA report on wall elements VIP and other insulation materials [16]. The data were used to calculate the cradle-to-gate climate change impact of a typical VIP, for subsequent use in the work presented here.

Description of Hollow Silica Nanospheres

The hollow silica nanospheres are produced at the Research Center on Zero Emission Buildings at NTNU and SINTEF Buildings & Infrastructure, in collaboration with SINTEF Materials and Chemistry. To the eye, the material looks like white powder. A picture of the spheres produced in a transmission electronic microscope is presented in Figure 1.

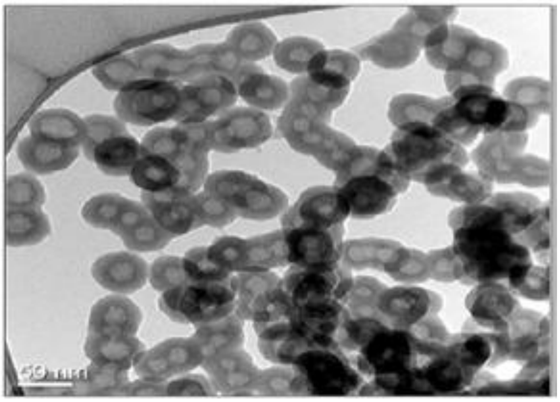

Figure1. *Transmission Electron Microscope image from of a sample of hollow silica nanosphere.*

Diameters and shell thicknesses can be varied. It is desirable to optimize the pore sizes to the point where the Knudsen effect is fully exploited [10]. If this can be achieved, it is theoretically possible to achieve thermal conductivities equal to VIP, without applying vacuum [10]. At the moment, spheres in the size range of 50-200 have been fabricated with success. The procedure of achieving hollow silica nanospheres is shown in Figure 2 and detailed below the figure. More comprehensive descriptions of the science and synthesis of hollow silica nanospheres can be found in , for instance, Gao et al. 2013 [17] and Du et al. 2010 [18].*Monodisperse polystyrene (PS) nanospheres were prepared and served as template for the subsequent growth of silica. For a typical synthesis, 1.5 g polyvinylpyrrolidone (PVP) was dissolved in 100 mL water under ultrasonic irradiation, and to this a solution 10 g styrene solution was added. The obtained styrene/PVP solution was then heated up to 70°C under constant stirring at 500 rounds per minute (rpm). Afterwards, 10 mL potassium persulfate (KPS) solution (0.15 gram KPS in 10 mL water) was added dropwise into the PVP/styrene solution to initiate the polymerization reaction. The polymerization reaction was kept at 70°C for 24 h. After the reaction, the obtained PS nanosphere suspension was cooled naturally to room temperature for further use. 6 g of as-prepared PS suspension and 4 mL ammonium hydroxide (NH_4OH) solution were added into 120 mL ethanol under constant stirring at 500 rpm. Then, 10 mL tetraethyl orthosilicate (TEOS) ethanol solution (50 vol% TEOS in ethanol) were slowly added. The system was stirred for 10–24 h to prepare core-shell typed nanospheres. After the reaction, the solid product was separated from the mother solution by centrifugation at 10000 rpm, and the obtained sediments were washed with ethanol twice and finally dried at room temperature. Hollow silica nanospheres were readily obtained by annealing the core-shell typed nanospheres at 500°C for 3 h as to combust the core.*

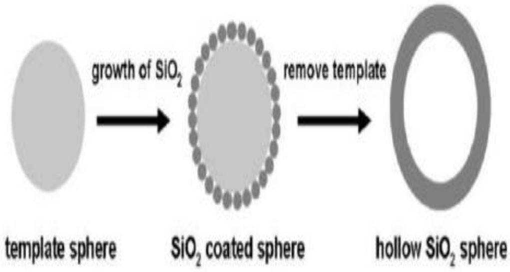

Figure2. *.A schematic drawing of the template assisted synthesis procedure of the hollow silica nanosphere.*

alternative route is suggested by Stephan Kubowicz at SINTEF Materials and Chemistry. The most important difference is that the polyacrylic acid (PAA) is used as a template instead of styrene. PAA does not have to be combusted, it can simply be removed by diffusion, when washing the nanospheres in water. It is important to recognize that this process is not fully optimized yet. As will be described in the following sections, several parameters of the spheres are affecting the thermal conductivity. These parameters need to be optimized in order to minimize the thermal conductivity of the material. Much experimental research remains in order to achieve the desired properties. Furthermore, the process is not optimized by means of an industrial scale production. An industrial production system may require substantial modifications on the fabrication route presented above. more research is needed on the final form of the material, e.g. how to make use of the spheres to create a building element with the desired properties. Nothing has yet been published on this step. It is partly unknown, partly restricted by intellectual property issues at this point. Referring to personal communication with BenteTilset at SINTEF Materials and Chemistry [19], the intension is to create a lightweight and flexible insulating mat. The mat will be superporous because it constitutes a high packing fraction of hollow silica nanospheres. Surface modification and binders will make the spheres stick together and add flexibility. Referring to personal communication with BjørnPetterJelle [8], responsible for the advanced material group at ZEB, it might also be possible to fabricate the spheres in the connected form directly, but this approach has not been studied yet. In any case, the spheres will be stuck inside the mat and cannot escape into the air, unlike aerogel particles in commercial aerogel fibremats. The locking of the nanoparticles in the material is important from a health perspective. The time dependent degradation caused by air diffusion of VIPs will not be a problem with the NIM, because it does not contain vacuum. However, moisture might cause problems, so the mat must be hydrophobic and durable. A flexible, rubberlike texture is desirable. It was not possible to get any details about the modifications or the substances required to obtain this. In conclusion, little information is available on the final properties, characteristics and production method for the NIM. A drawing of the future material, freely imagined by the candidate and realized in SolidWorks by design student Tori KlakeggMæhlum, is presented in Figure 3.

Figure3. *A projection of what the NIM might look like as a complete, ready-to-use insulation material.*

Silica aerogels are chemically inert, highly porous ceramic materials[20-23]. They are the product of a sol-gel process, whose final stage involves extracting the pore-filling solvent with liquid CO_2. The latter is gasified supercritically and is vented off, leaving behind a very low density solid (0.002- 0.8 g cm^{-3}), with the same volume as the original hydrogel and a chemical composition identical to glass. Aerogels have been considered for thermal insulation,[24] catalyst supports, [25] or as hosts for a variety of functional materials for chemical, electronic, and optical applications[26]. Practical application has been slow though, because aerogels are brittle and hygroscopic, [27] absorbing moisture from the environment which leads to structural collapse due to the capillary forces developing in the pores. The poor mechanical properties of silica aerogels notwithstanding, many plastics are reinforced with glass. For example, several thermoplastics for injection molding are supplied preformulated in glass-fiber-containing pellets, and long glass-fiber-reinforced polyurethane rods are considered as a lightweight, noncorroding alternative to steel in architectural construction[28] Glass fiber does not improve the strength of silica aerogels, [29] but because glass/polyurethane composites are strong enough to substitute for steel, we decided to focus on the interface between those two materials, reasoning that if a similar synergism could be engineered into the structure of monolithic silica aerogels, it would result in strong, very low density materials. Base-catalyzed silica aerogels consist of large voids (mesopores, ~50 nm in diameter) in a "pearl-necklace" network of microporous, so-called *secondary* particles,[30] which are the smallest entities visible in Figure 4 (5-10nm in diameter). Those particles are connected by "necks" formed by dissolution and re-precipitation of silica during aging[31] Reasonably, the strength of monolithic aerogels could be improved by making the necks wider.

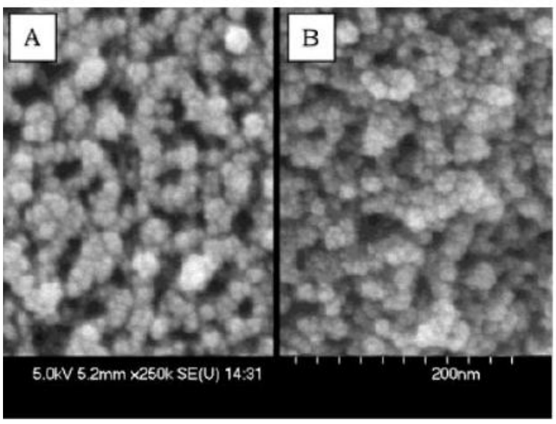

Figure4. *SEM images from randomly selected spots in the interior.*

To accomplish this with minimum addition of new material, the contour surface of silica has to be used as a template for the deposition and growth of the interparticle cross-linker. Silica is surface-terminated with silanols (-SiOH). Polyurethane, (-CONH-R-NHCOOR¢O-)*n*, is formed by the reaction of a diisocyanate (OCN-R-NCO) and a diol (HO-R¢- OH)[32]. A similar reaction of an isocyanate with glass-surface silanols (-Si-OH) modifies glass fibers,[33] chromatographic silica absorbents,[34] and sol-gel derived particles.[35] In a typical procedure, a diisocyanate cross-linker is introduced in the aerogel structure as follows. Hydrogels (1 cm diameter, 3-4 cm long) are prepared from tetramethoxysilane via a base-catalyzed route[36, 37] and are aged for 2 days at room temperature. Subsequently, according to a postgelation doping protocol,[37, 38] pores are filled with a diisocyanate (di-ISO) solution by washing successively with methanol, propylene carbonate (PC), and PC/di-ISO (4 - 8 h in each bath). The di-ISO employed was poly(hexamethylenediisocyanate) (Aldrich)[39]. The vials containing the gels in the last bath are heated at 100 °C for 3 days, then are cooled to room temperature. The solution is decanted, and the gels are washed with PC (1 × 8 h), PC/acetone (1:1, 1:3, v/v; 1 × 8 h each), and acetone (4 × 8 h) and are dried supercritically.

Conclusion

Green Nanocomposites can use very good in the Architecture. Today the several green materials have produced by European and American companies. These materials have good chemical and mechanical properties.

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