



Focus Report 2010  
Aerogels

---

April 2010

Authors: Matthias Werner, Ingo Barbré (NMTC, Berlin);  
Leif Brand (VDI Technologiezentrum, Düsseldorf)

Contact: [werner@nmtc.de](mailto:werner@nmtc.de)  
[brand@vdi.de](mailto:brand@vdi.de)

ObservatoryNANO

Dr. Mark Morrison  
Institute of Nanotechnology  
Lord Hope Building  
141 St James Road  
Glasgow G4 0LT  
UK

[www.observatoryNANO.eu](http://www.observatoryNANO.eu)

## Index

## Chemistry &amp; Materials; Focus Report 2010: Aerogels

Executive summary .....	3
Introduction .....	5
Definition .....	5
Keywords .....	5
Overview .....	5
Scientific and technological aspects .....	6
State of R&D .....	6
Additional demand for research .....	12
Applications and perspectives .....	13
Current situation within the EU .....	21
Economic aspects .....	21
Market description .....	21
Nanotechnology impact .....	23
Drivers and barriers to innovation .....	24
Relevant product segments and applications .....	24
Short application description .....	25
Boundary conditions .....	26
Product examples .....	26
Economic information for present products .....	29
Profiles of selected key companies .....	31
References and Literature .....	33

## Chemistry & Materials; Focus Report 2010: Aerogels

### Executive summary

Aerogels can be characterised as materials with the lowest density of any known matter. Aerogels are a heterogeneous class of porous, solid materials which exhibit a number of extreme properties. They are predominantly known for their extremely low densities ranging from 0.0011 to  $\sim 0.5 \text{ g/cm}^3$ . Silica aerogel in particular is only three times heavier than air. Typically aerogels consist of 95-99 % air or vacuum in volume. Essentially an aerogel is a dry, low-density, open-porous, solid framework of a gel with pore diameters in the range of 1 to 100 nm in diameter. Aerogels represent a nanomaterial with promising application possibilities although, technological developments and market maturity remain challenging issues.

From an ecological point of view aerogels offer excellent thermal insulation properties, for example in the oil and gas industry or in architectural engineering. In the latter, they are meeting a long term trend towards more energy-efficient construction. The energy consumption of buildings in central Europe is around 20 litres of heating oil per square metre per year, whilst the current standard for energy efficient buildings is about 7 litres and pilot projects are already being implemented for "3-litre houses". Consistent thermal insulation is a crucial issue in that respect. Due to the optical transmission of aerogels there are also new opportunities for architectural design of translucent, heat-insulating building facades. Not only in architectural engineering but also in a variety of industrial processes (e. g. high temperature and cryogenic processes) and in household appliances aerogel based insulation materials offer considerable application potential. That holds true also with respect to noise protection requirements.

From a technological perspective aerogels have potential in various areas; for example, in microelectronics, where an accelerated miniaturization of integrated circuits requires materials with lower dielectric permittivity than  $\text{SiO}_2$ . Here, aerogel films are a likely candidate. In power engineering, catalysis, and sensors materials with large specific surfaces, which can easily be doped with functional substances, are required. Aerogel materials offer these properties. This also applies to controlled release applications in agriculture and pharmaceuticals. Due to the low density of aerogels further application possibilities as a basic lightweight material e. g. in automotive technology are opening up. This is especially true if aerogels with high mechanical stability may be produced at low cost in the future.

With respect to market attractiveness, positive developments in the long term may be expected. Aerogels offer potential in a variety of market segments, ranging from volume markets at the raw material level (including fillers, adsorbents, granules for cosmetics, pharmaceuticals, and construction machinery) up to the component level (including windows for buildings, electrode materials for batteries, and capacitors). The major issue is an economically competitive production. However, in the medium term aerogel materials could achieve a significant share of the global market for thermal insulation products. Low cost aerogel materials could also be utilised as fillers for various products in specialty chemistry and pharmaceutical industry (rubber, toner, detergent, cosmetics, pharmaceuticals) to compete with conventional products,

such as Aerosil. In addition, special applications for high-tech products (including sensors, catalysts, micro electronics, and electronic engineering) are being investigated. Aerogel composites utilised as highly efficient catalysts give rise for obtaining high economic savings in the manufacture of chemical products.

The global market for aerogels accounted for \$82.9 million in 2008 and it is expected to reach \$646.3 million in 2013 with a compound annual growth rate (CAGR) of 50.8%. The market will be driven by thermal and acoustic insulation applications. Currently this segment accounts for 70% of the total aerogel revenues. However, up to now only a few consumer products have been commercialised with a focus on high-tech products. This is due to high manufacturing costs and high dust production during aerogel material installations. Based on a new, patented manufacturing process developed by Aspen Aerogels, Inc. the problem of costly fabrication should be overcome.

The market for aerogels is quite small and only a limited number of manufacturers play a key role in this market segment. Therefore, changes in companies activities will have an impact on both manufacturing and sales distribution.

The degree of novelty of the technology itself is considered to be low; the production technology is based on the classical sol-gel-process. However, there is still potential for optimization with regard to production processes and new combinations of materials.

The patent situation has been considered unfavourable. A variety of patents are held by US-based companies. That holds especially for Cabot, which acquired the former aerogel activities of Hoechst/Aventis underlining the current weakness of the European market position.

The product potential may be classified as high. Key factor for commercial success is an economic production of aerogel materials. On the basis of additional material modifications and material doping a host of new products in specialty chemicals could be further developed without high investment costs in the medium term. However, for chemical companies even destructive competition effects with respect to other product lines, such as aerosol, could partly occur.

Currently a relatively low number of companies is engaged in aerogels. Apart from some niche players, the most important player, is Cabot, which has achieved a broad commercialization of aerogels and manufacturing processes on the industrial scale.

Some application areas of aerogels are characterised by a strong dependence of customers and system developers. In these areas, market collaborations will be crucial.

The market framework for aerogel products may to be positively assessed. In particular, in an ecological perspective aerogel products may improve energy and resource efficiency. On a long run, improvements with respect to noise insulation, optimised pharmaceuticals, or a sustainable water infrastructure can be expected. Regarding the supply of raw materials, there are no limiting factors, from either an economic or an ecological point of view.

## Introduction

### Definition

Aerogels are highly porous solids with an inner surface of 600 to 1000 m<sup>2</sup> per gram. With a bulk density between 0.003 and 0.35 g/cm<sup>3</sup> they are considered as the most lightweight existing solids. In addition they also show the lowest thermal conductance of all solids. Aerogels consist of nano-particles arranged in a highly porous three-dimensional network with pore diameters varying between a few nanometers and some micrometers. Typical pore diameters are in the range of approximately 10 nm. The pores typically constitute about 95 % of the material volume. Aerogels are often nicknamed as "frozen smoke", "solid smoke" or "blue smoke"; the latter due to its optical transparency and light scattering properties.

### Keywords

Aerogel, Nanofoam, "frozen smoke", "solid smoke", "blue smoke"

### Overview

The term "aerogel" is composed of "air" and "gel". A gel consists of two components, a gel scaffold and a filling medium. In case of the aerogel the filler is simply air. Aerogels are firm materials of extremely low density, large open pores and a large inner surface. As a result they have exceptional physical properties such as an extremely low thermal conductivity, low sound speeds, and high optical transparency. However, the technical use of these unique characteristics is still in the early stages of development. Although the basic principles of aerogels have been documented for some decades, R&D has only intensified during recent years and the range of possible applications has been expanded. However, practical utilization is mainly restricted to silica aerogels in the construction sector, for example for house facades.

The term "aerogel" refers to the inner structure rather than to the type of the materials. Thus, it is possible to fabricate aerogels from a variety of different materials. Inorganic, organic and hybrid aerogels have been manufactured, in addition to aerogel composites and fiber reinforced aerogels. Aerogels and their production processes thus principally offer a large variability and adjustability with respect to the specific application in view.

The spectrum of potential applications is quite broad. It is ranging from architectural engineering, textiles and household appliances via chemical and environmental engineering, energy storage, and automotive applications up to more exotic applications like particle collectors for interstellar dust collection or lightweight heat shielding materials for space shuttles.

However, it is mainly the low mechanical stability of some aerogel types and the high production cost, which is preventing larger commercialisation. During recent years considerable progress has been achieved in that respect. More efficient production methods and more stable carbon aerogels have been developed for example.

Based on a cheaper industrial production process the American company Cabot has established a large scale production in Frankfurt/Germany.

Today a number of companies exist that are commercialising aerogels for specific technical applications. They are predominantly US-based (e. g. Cabot, TAASI, Nanopore, MarkeTech International, Aspen Aerogels). But even European companies like the Swedish Airglass are addressing niche markets.

### Scientific and technological aspects

To enable a comparable evaluation of nanotechnology related applications, the following "Technology readiness Levels" (TRL) have been defined for scientific or technological evaluations within ObservatoryNANO reports:

- TRL 1: "basic research"
- TRL 2: "applied research"
- TRL 3: "prototype / lab device"
- TRL 4: "market entry"
- TRL 5: "mature market" (mass- or established niche markets)

The TRLs will be used to classify specific applications according to their technological readiness.

### State of R&D

Aerogels may in principle consist of metal oxides, mixtures of metal oxides, polymers, carbon or several other materials. They may be manufactured by hydrolysis of soluble precursors in a sol-gel process. By addition of dopants the chemical composition of aerogels may widely be varied. Aerogels made of quartz, that is silica aerogels, are well known and the most examined so far. They are inorganic polymers and their molecular structure forms a silicon/oxygen scaffold. Aerogels contain a multiplicity of cavities filled with air. Because of their extremely low density (only about three times the density of air) they show a number of specific properties making them of particular interest for different applications such as thermal or acoustic insulation. The production of silica aerogels as well as further potential applications, such as drug carriers, have also been examined for some years.

Carbon aerogels and composite aerogels with metallic or polymere components are also gaining interest. There is a technical demand for aerogels that are mechanically stable and more water resistant than silica aerogels for example, which re-convert to a gel once getting in contact to water.

More recent developments therefore tend more toward organic aerogels. Cellulose aerogels for example show a very high strength but are considerably cheaper to produce. In addition they are bio-degradable and easier to handle in particular for volume usage such as building, air-condition or refrigerator insulation.

### *Inorganic aerogels*

Almost all metal or semiconductor oxides can form gels and thus be manufactured to aerogels. Beside silicon- or silica aerogels other inorganic aerogels for example based on titanium, zirconium, tin, aluminium, vanadium, chromium, iron, tantalum, molybdenum or niobium are being synthesized in smaller quantities.



Fig. 1 Silica aerogels (University of Würzburg)

Also binary and ternary oxidic aerogels are being manufactured. Furthermore it is possible to dope aerogels with different materials such as noble metals, which are dispersed within the matrix structure. This is of particular interest for catalytic applications. However, a disadvantage of these materials is their brittleness which is due to their ceramic nature.

#### *Organic aerogels*

Beside inorganic aerogels it is also possible to synthesize aerogels from organic polymers. For that multi-functional organic monomers are polymerized in a dilute solution. Resorcinol/formaldehyde and melamine/formaldehyde have been the first monomer mixtures used. Based on a catalyst such as sodium carbonate or caustic soda the gelling process has been initiated. By supercritical drying these gels can be converted into pure organic aerogels almost without contraction. Other processes are based on the polymerization of furfural with phenolic resins (phenol/formaldehyde)<sup>1</sup>.

Organic aerogels are less brittle, more stable and mostly more light-weight than their inorganic counterparts. Besides they are even better thermal insulators. The thermal conductivity of a resorcinol-formaldehyde aerogel of a density of  $0.15 \text{ g/cm}^3$  at  $27^\circ\text{C}$  is only  $0.012 \text{ W/mK}$ , which is the lowest value ever measured for an evacuated material. The thermal conductivity of even CFC-blown polyurethane foams stays above  $0.02 \text{ W/mK}$ , whereas foams without CFC filling only reach  $0.03 \text{ W/mK}$ .

Organic aerogels can be converted to deep black carbon aerogels by pyrolysis, that is heating in a de-oxygenated environment. This process develops extraordinary mechanical stability but also electrical conductivity. Due to their low electric resistance (less than  $40 \text{ m}\Omega \text{ cm}$ ), their adjustable pore size distribution (1-50 nm), and their large specific surface, carbon aerogels are very suitable for use as an electrode material. Their extraordinarily large surface to volume ratio allows for an enhanced electrical charge storage compared to conventional capacitors. Thus, carbon aerogels allow for the fabrication of supercapacitors with extremely high charge

density. An additional advantage compared to carbon powders or carbon fibers for example is their monolithic component structure.

Organic aerogels are also being manufactured from cellulose. At the beginning of the decade researchers of the University of Oklahoma combined an aerogel fabrication technique with a method for the reinforcement of paper. They used cellulose-acetate for the scaffold. The material was hardened by a chemical process which is also utilized for paper reinforcement or the conversion of natural rubber to ebonite. Based on this process a ten-fold mechanical hardness compared to conventional aerogels could be achieved.<sup>2</sup> The aerogel weighed only about 0.35 g/cm<sup>3</sup>. Due to their properties NASA was expected to utilize the cellulose aerogels as a protection coating for space shuttles.

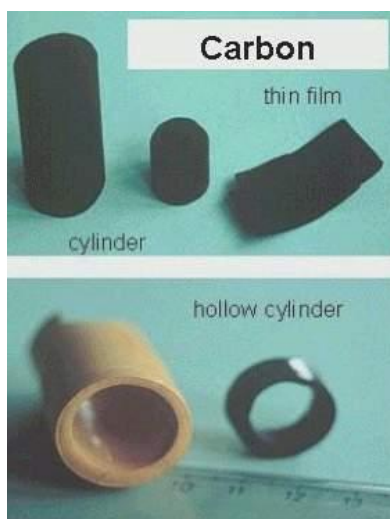


Fig. 2 Different components made of carbon aerogels<sup>3</sup> (University of Würzburg)

Whereas R&D-activities have led to first market entries of silica aerogels products, the development of organic aerogels is still at an early stage. In the future there is evidence for the production of aerogels that are based on more common materials than melamine or resorcinol; perhaps there will be polystyrene or polyethylene aerogels may be anticipated.

#### *Hybrid aerogels*

Researchers try to develop inorganic-organic hybrid materials even in the case of aerogels in order to enhance and optimise the spectrum of properties and possible applications. The insertion of organic substituents into SiO<sub>2</sub>-aerogels allows for improvements concerning their hydrophobicity and elastic properties. The synthesis of such hybrids is mostly directly integrated into the sol-gel process.

Improvements have been achieved some years ago; for example at the University of Missouri-Rolla glass-fibre reinforced polyurethane aerogels were manufactured in 2002. The material exhibited considerably optimized mechanical strength. The aerogel was up to 100 times more break resistant compared to the original silica aerogel and completely inert against humidity.<sup>4</sup>

It is also possible to insert organic dopants into inorganic aerogels. An example is the doping of quartz-aerogels with soot; they exhibit optimised thermal insulation properties due to soot being an effective absorber for infrared thermal radiation. Other organics such as laser-dyes

(rhodamines, fluoresceine etc.) may also be smoothly dispersed within inorganic aerogel matrices.

### *Aerogel layers*

There are a number of applications in electronics, sensors, catalysis, and medical engineering amongst others where it is desirable to apply aerogel layers or coatings. The fabrication of such coatings is based on dipping or spin-coating.

#### *Silica aerogel films as intermetallic dielectrics in electronics:*

SiO<sub>2</sub>- aerogel films are being discussed as future "low-K-dielectrics" for the isolation of metallic interconnects in microelectronics. The increasing miniaturisation of integrated circuits creates demand for materials substituting the widely utilized silicon dioxide, which loses its isolating properties below a minimum layer strength. The fabrication of aerogel thin films is based on the spin-coating of a silicon substrate with a sol consisting of tetraethoxysilane/iso-propanole.<sup>5</sup> The solvent is removed by a supercritical drying process avoiding volume losses of the material.

#### *Layers of aerogel-TiO<sub>2</sub> on metal-substrates for medical implant materials:*

New syntheses for nano porous ceramics have been developed for specific applications such as membranes, multi-layer components or nano structured composite materials. The sol-gel process is of particular interest due to the possibility of achieving either dense or porous ceramic layers onto different substrates. Layer thickness and porosity may be varied by control of the synthesis conditions, process paths and the composition of the organo-metallic precursors.<sup>6,7</sup> The application of organo-metallic precursors and the sol-gel technique also enables the fabrication of titanium based coatings. Variation of the amount of solids and the conditions of hydrolysis, drying or peptisation during synthesis result in either dense, transparent TiO<sub>2</sub>-xerogel layers (see below) or highly porous aerogel layers with adjustable specific surface and porosity. Repeated dipping in different sols and under different drying conditions may deliver a material with a gradual porous TiO<sub>2</sub>-surface which is suitable for utilization as medical implant material.

### *Fabrication methods*

Aerogel production is based on two major steps;<sup>8</sup>

- fabrication of a gel penetrated with solvent
- removal of the solvent by a specific drying process

Hence, aerogel production always requires the production of a gel filled by liquid components. Silica gel is quite easily achieved; it consists of a SiO<sub>2</sub>-scaffold that is supported by water. In a second step, for the removal of the liquid, the gel has to be dried, which requires a suitable process design; drying under ambient conditions destroys the gel-scaffold due to capillary forces in the small cavities at the liquid-air-surface. The gel shrinks considerably and the final product will consist of numerous fragments of the original gel-corpous. Such ambiently air-dried aerogels are called "xerogels".

The shrinkage of the gel-corpous may be drastically reduced by adjusting the process parameters in a way that overcomes the border between the liquid and the gas phase. That may be

achieved by supercritical drying resulting in the desired nanoporous materials of ultra-low density of typically 0.05 to 0.1 g/cm<sup>3</sup>. Due to the small pores, the specific or internal surface is extremely high and achieves values of 500 m<sup>2</sup>/g and above. Silica aerogels fabricated by supercritical drying achieve densities down to 0.02 g/cm<sup>3</sup> according to pore fraction of 99 %. However, supercritical drying is an expensive fabrication step and widely un-suitable for industrial volume production.

Based on these findings, the development of technical production process and initial steps of commercialisation were made in the early 1990s, involving also European companies like BASF, Hoechst and Henkel. Several companies stopped the commercialisation of aerogels. However, in recent years, other players with improved production methods have emerged. These include e. g. Airglass (S), Cabot (USA) TAASI (USA), Nanopore (USA), Brand Tech International (USA) and Aspen Aerogels (USA).

Following this new or modified production methods have been developed to remove the pore liquid from the gels in ways different from supercritical drying, and thus opening up new ways for volume production.

Some methods for the fabrication of aerogels are presented below.

*Kistler's method:*

The oldest known method for aerogel fabrication is due to S. S. Kistler at the Stanford University in the early 1930s.<sup>9</sup> Kistler's first aerogels emerged from a sodium silicate solution, which gelled within 24 hours after being mixed with HCl. Washing with water resulted in an "aquagel", subsequent treatment with alcohol transformed it into an "alcogel". Evaporation of the alcohol at the surface of the gel-corpous causes the development of concave menisci in the tiny pores. Progressing evaporation causes the menisci to retreat into the gel-corpous leading to an overall shrinkage of the gel due to surface tension. To avoid these surface tensions Kistler dried the gel within a pressure container or an autoclave. Increasing temperature and pressure to above "critical" values causes the formation of a "supercritical fluid" out of the liquid and its vapour overcoming the separation between liquid and gas, each molecule can move freely with no boundary between liquid and gas, and hence no more surface tension. The supercritical fluid is then slowly blown off from the autoclave. After cooling, the aerogel can be taken out. The critical parameters of the drying process depend on the liquid used. A gel in methanol, for example, requires temperatures of about 240 °C and a pressure of about 81 bar. Since there are no tension forces effecting on the gel-corpous, it retains its original size and shape. The quartz aerogels manufactured by Kistler had a density of 0.03 to 0.3 g/cm<sup>3</sup>, which corresponds to porosities of 98 to 86 %.

Kistler succeeded in drying gels without shrinkage. However, his manufacturing method was cumbersome and slow. This holds especially for washing the aquagel and the subsequent replacement of water by alcohol. This solvent-replacement however, was unavoidable as water would re-dissolve the gel structure at high temperatures.

*Teichner's method:*

In the end of the 1970s French researchers managed to shorten the fabrication process from weeks to several hours by applying alcoxysilanes in the sol-gel-process. The group of S. J. Teichner<sup>10</sup> started with tetramethoxysilane (TMOS) and a metered amount of water. Adding a

catalyst resulted in the formation of silica and methanol. Water splits off the silica and the resulting SiO<sub>2</sub> groups form a gel. Structure and density can be controlled by the catalyst, the pH and the ratio of the raw materials used, particularly the amount of the methanol solvent.

Instead of the toxic TMOS meanwhile tetraethoxysilane (TEOS) is used for aerogel fabrication.<sup>11</sup>

*Process improvements and industrial production methods:*

By utilisation of supercritical media such as methanol or CO<sub>2</sub> for gel drying additional process improvements had been achieved within the 1980s. The critical point e. g. of methanol is at 239.4 °C and 80.9 bar. To overcome the phase boundary, which would lead to meniscus formation within the pores, pressure and temperature of the aerogels have to exceed above the critical point. Subsequently the vapour has to be drained off by isothermal expansion forcing the methanol to diffuse from the gel structure. Due of the finite viscosity of the methanol, pressure lowering should be driven slowly in order to avoid a pressure gradient, which can lead to rupture. Typical rates of pressure lowering are 5 to 10 bar/h.<sup>12</sup> Utilisation of supercritical CO<sub>2</sub> as fluid instead of alcohols makes the process much more secure, as CO<sub>2</sub> is non explosive and allows for lower reaction temperatures. The process of supercritical drying with fluid CO<sub>2</sub> is performed within an autoclave at 80 hPa and a temperature of 35–40°C. However, the time consuming exchange of alcohol by CO<sub>2</sub> is a disadvantage.

On this basis, some companies such as BASF, Henkel, Thermolux, Aerojet, Airglass developed large-scale production processes. For experimental purposes BASF manufactured aerogels in granular form instead of rectangular blocks already in the early 1990s. For that sodium silicate and an acid was sprayed into a washing solution by a nozzle. The supercritically dried aerogel pellets had a diameter of 1-6 mm and a density in the range of 0.2 g/cm<sup>3</sup>. Such pellets could be produced cheaper than blocky shaped aerogel. The aerogel pellets could be loosely filled e. g. into the gap between windowpanes. The granules, however, have somewhat poorer optical and thermal properties compared to block aerogel. Optical reflection for example is increased due to the multitude of spherical surfaces, which prevents transmission. The filler also affects light diffusion and is less transparent. BASF produced these aerogels under the trade name "BASOGEL" until 1996.

There has been intensive research for technically simpler and cheaper production methods since years in order to make aerogels commercially interesting. For this reason one tries to bypass the most costly and risky production step, the supercritical drying. Synthesis methods have been developed that allow drying based on conventional laboratory equipment. A drying process under atmospheric pressure and at relatively low temperatures (e. g. between 20-180 °C) has been developed and is now known as "subcritical drying". Addition of monomers results in a strengthened and stiffened gel network, thus avoiding shrinkage during the drying process.<sup>13</sup> In particular, companies like Hoechst and Nanopore (USA), utilized this new method which soon led to first success.

It was the development of a new process by Siemens Axiva based on conventional drying methods that enabled industrial volume production of aerogels. To optimize the mechanical properties Siemens Axiva furthermore developed a specific forming process. Supported by computer simulation tools, Siemens Axiva managed to develop a patented mixing nozzle which

allowed for the fabrication of silica gel particles of narrow size distribution, extremely good flow properties and a very high abrasion resistance.

The team of Siemens Axiva, which was a part of Hoechst AG (later Aventis) developed this process in the early 1990s. With the acquisition of the Aventis aerogel research division in 1998, the US company Cabot gained the patent rights for this process of aerogel manufacture in industrial scale. In addition, Cabot took advantage of a pilot plant in which the process had already been tested on a pilot scale and first samples were produced.

After intensive testing Cabot decided for an industrial production and the establishment of a semi-works plant in Frankfurt (Germany) with a capacity of around 1,000 tonnes per year.

The design and construction of the plant as a so called "first-of-its-kind" system was executed by made by Siemens Axiva. Following the mechanical completion and handover it was in September 2002 when aerogels were produced for the first time based on an innovative, economical process on an industrial scale. Meanwhile Cabot built up a plant with a capacity of 10,000 tonnes per year.

#### Additional demand for research

In recent years considerable progress has been achieved concerning both the mechanical stability (brittleness) of aerogels and production cost. More stable carbon aerogels have been manufactured for example and more efficient production methods have been developed. However, reliable volume production at a reasonable price still remains an issue and represents a major drawback particularly for low-cost mass markets. Here aerogels, such as silica aerogels, are mostly not competitive compared to conventional materials.

The same holds for the aspect of mechanical stability, which is the second major obstacle for commercial applications. The predominantly applied silica aerogel is very fragile and brittle and often requires further processing or modification prior to real applications. Production of aerogel granules is one approach; however, granules are associated with deteriorated properties, such as the insulation and transparency characteristics, compared to the bulk material. The approach of reinforcing the aerogel by hybridising the material and fabricating aerogel composites is promising. However, it makes production more expensive and thus limits its application to higher value products and applications.

In general there are a number of established conventional materials competing with aerogels.

#### *Functional requirements*

As a result of the issues highlighted previously aerogels are increasingly pushed towards value and niche market applications with specific requirements. One example is the lifestyle sector; due to their low weight and the tremendous strength at least organic reinforced aerogel composites allow for the production of ultra lightweight products. For tennis rackets, for example, it is possible to increase the frame stiffness without increasing its weight.

Another special application is the utilisation of aerogel material in pipelines including flow lines and risers, which are used in deepwater offshore gas and oil fields. These require a high thermal insulation performance in combination with small sizes and low weights; however, there is also the need for cost reduction and a minimisation of hydrate or wax formation during oil or

gas transportation. Aerogel materials are able to meet these requirements due to the range of suitable material properties they offer.

A broad range of military applications have also already been realised or are conceivable. They make use of typical characteristics like high temperature thermal insulation, cryogenic thermal insulation, IR suppression, sound absorption, and fire suppression. Additionally, tests have been carried out with bomb-proof armour for military vehicles and troops<sup>14</sup>.

### Applications and perspectives

Due to their nanostructure and high porosity aerogels have a number of interesting properties making them promising for technical applications. Among these outstanding properties are:

- Extremely low thermal and acoustic conductivity making aerogels suitable for applications in architectural engineering, chemical engineering, automotive engineering, textile technology and other applications;
- Optical transparency / translucency for applications in architectural engineering (insulating windows and facades) and sensors;
- Very low permittivity for applications in electronics;
- Extremely high porosity and large inner surface for applications in chemistry, pharmaceuticals, energy and environmental engineering;
- Very low density which, in combination with enhanced mechanical properties of organically modified aerogel for example, can be utilized for ultra lightweight materials in aerospace or automotive applications; and
- High brittleness of silica aerogels could be utilized in materials that absorb kinetic energy; examples include helmets, and car bumpers.

In the past, aerogels have been used primarily for specialized scientific applications, such as particle detectors in high energy physics (for example DESY, CERN) or for the examination of solidification in forming and casting processes. The main barrier to widespread commercial application of aerogels are their relatively high price. Other factors limiting technical applications are the low mechanical stability and fragility of the material as well as its limited optical transparency for applications in insulating windows. Regarding mechanical stabilisation significant progress has been made in the form of organically modified hybrid aerogels. Also in terms of a cost-effective production the economic threshold of an extended large scale production has been reached for specific applications. Product options for a variety of applications are opening up.

A number of applications will be discussed in the following:

#### *Thermal insulation (TRL 4 to TRL 5)*

Silica aerogels are characterized by excellent insulation against heat conduction and convection. Concerning thermal radiation and light, however, they are almost transparent. The insulating properties of aerogels are significantly better than those of conventional insulation materials such as expanded polystyrene. Organic aerogels, such as those based on resorcinol-formaldehyde sometimes have even lower thermal conductivity than silica aerogels.

Aerogels are principally suitable as thermal insulation materials in a variety of applications:

- Architectural engineering (windows, translucent facades, passive solar collectors etc.);
- Household appliances (refrigerators, coolers, thermal springs, electronic devices, etc.);
- Textiles (thermo jackets);
- Chemical process engineering (cryogenic processes, high temperature processes, forming and casting);
- Automotive (engine, exhaust system); and
- Space/astronautics (satellites, space shuttles and probes).

Application as a highly effective thermal insulation material in buildings is among the most promising markets for aerogels; the market for Western Europe is estimated in the multi-billion euro range. Beside the facade insulation aerogel materials are also principally suitable for applications in windows, due to their high transparency (more than 90% light transmission). As part of an EU project the Swedish company Airglass developed a prototype integrated window already some years ago, in which a monolithic aerogel layer was sandwiched between two sheets of glass and was then evacuated to 50-100 hPa.<sup>15</sup> The prototype window showed a similar visual quality as ordinary glass and a thermal loss coefficient of less than 0.4 W/m<sup>2</sup>K. In the medium term aerogel windows could compete with other insulating double- or triple-glass window panes. In addition to lower heating costs, another advantage is the reduced thickness of aerogel windows compared to conventional insulating windows. The commercialization of aerogel windows has been driven forward, particularly by Airglass who are developing insulating windows, fire safety glasses or solar collectors. However, the high production costs and the low mechanical stability (fragility) of aerogel materials remain obstacles for commercial applications.

To prevent problems caused by the brittleness of aerogel windows other manufacturers have focused on granular materials. However, due to their lower optical transparency they are more suited for translucent building facades or skylights. Producers of aerogel granulates include Cabot and Aspen Aerogels. Aerogel windows of this type are based on double glazing with aerogel granules filled in between.

Incident daylight gets diffusely distributed by aerogel windows and therefore they provide uniform room lighting. The optical and thermal properties of aerogel windows may be varied over a wide range by adjustment of the thickness of the aerogel layer and the selection of the type of glazing. Systems of daylight illumination of working and living areas as well as large area glazing have been identified as suitable applications due to the scattering and thermal insulation properties of aerogels. As a transparent insulating material aerogels offer new future possibilities in building architecture and design. Various pilot applications as transparent building facades have been implemented in Germany, Switzerland or the United States.

For an optimized passive utilisation of solar energy, thermal insulation materials made of aerogels can be positioned in front of dark facade walls. Due to the light transmission properties of the aerogel layer the dark wall absorbs the solar heat and conserves it due to the excel-

lent thermal insulation of the material. The thermal energy largely diffuses through the wall into the interior of the building

Architectural engineering aerogels may also be utilized as thermal insulation in household appliances such as refrigerators or ice boxes. Aerogel based insulations have been commercialised under the brand "Barrier Ultra-R™" by the company Firma Glacier Bay.<sup>16</sup>

Aerogels have also been developed for super-insulating thermo jackets, which are being commercialised by the fashion brand Hugo Boss. Aerogel filled clothing (Spaceloft™) and textile fibers (Aerotex<sup>T</sup>) are produced by Aspen Aerogel.<sup>17</sup>



Fig. 3: Thermo jacket with aerogel insulation. (Aspen Aerogel)

Chemical engineering is another promising application area for aerogel based thermal insulation for both high and low temperature processes. New efficient insulation materials may reduce energy consumption in a variety of industries such as chemistry, glass/ceramics, metal, and petro-chemical industries. Aerogel based high temperature insulation materials have been explored in the Lawrence Berkeley National Laboratory in California under funding of the U.S. Department of Energy (DOE).<sup>18</sup>

A special application is forming and casting. Low thermal conductivity, heat resistance and transparency are making aerogels interesting materials for molding engineering and freezing research. The transparency of silica aerogels allows for the direct observation of filling processes in shell-molds and a direct diagnosis and analysis of cooling and freezing with IR-cameras. Utilisation of silica aerogels enables new freezing processes and according in-situ analysis. The utilisation of polymer aerogels enables newly designed forming and casting techniques.

Light weight thermal insulations are also of interest for the automotive industry; for example as engine compartment insulation or combined thermo-acoustic protection for exhaust systems.

In astronautics aerogel materials have been used for various thermo insulations for instruments and probes.

### *Acoustic applications (TRL 2)*

Aerogels have a number of specific acoustic properties. The speed of sound is only 100-300 m/s and thus considerably slower than in air or in conventional quartz glass and it actually decreases with increasing environment pressure, which is a remarkable property.

Low sound velocity and low density furthermore result in an equally low "acoustic impedance", which physically is the product of both quantities. Due to these properties aerogels are investigated for applications in noise protection. In particular in building, aerogels could be applied as combined thermal and acoustical insulation materials; for example in floor insulation. Especially in the range of low frequencies aerogels offer an improved sound insulation compared to conventional insulation materials. Due to the high insulation effect the thickness of the insulation layers could be reduced significantly resulting in lower space requirements within the building.

Moreover, aerogel based sound insulation is also conceivable in traffic related applications (automobile, aircraft, noise barriers) is.

Aerogel materials as membranes in electrodynamic converters for high-quality loudspeaker boxes are already ready for market.

Due to the low impedance of aerogels, which lies between the widely differing impedances of piezoelectric transducers, and air, a thin layer of gel at the surface of the converter could serve as a buffer, and thus significantly reduce the reflection losses at this surface. Hence, the efficiency of piezoelectric transducers, which are often used for distance measurement in cameras and robotic systems, can be significantly increased. However, the suitability of aerogels for this application has not yet been proved.

### *Catalysts (TRL 3)*

Aerogels are particularly suitable as catalysts and catalytic substrates. This is because of their extremely large internal surface, which is easily accessible due to its open porosity, the large pore volume, and its temperature resistance. A catalyst's activity is strongly dependent on its surface. Nearly all oxides relevant for catalytic applications may be manufactured as aerogels. That holds also for binary and ternary compositions, mixtures of metal oxides and metal particles on oxide substrates. In addition aerogels may be fabricated as powders, granules or in monolithic form, either amorphous or with crystalline fractions. Catalytic metals may be smoothly deposited in aerogel scaffolds by chemical vapour infiltration processes, which considerably increase the active surface. Aerogel research in catalytics has been performed since the early 1970s. Considerable progress has been achieved since then and numerous catalyst systems have been examined; an example being catalysts for PEM fuel cells. Catalyst particles smoothly distributed over the aerogel scaffold could significantly reduce the amount of platinum required, which is a considerable factor for commercial applications of PEM-cells in vehicles. Aerogel based metal catalysts also enable the synthesis of carbon nanotubes, a method which has already been patented.<sup>19</sup>

### *Electronics (TRL 1 to TRL 2)*

As the production of increasingly faster and more complex computer and memory chips reaches its limits with the means of existing chip design and the materials used. Researchers are therefore looking for new methods to make chips smaller and more powerful. Aerogels

represent an option as innovative low-K dielectrics, as memory devices, or in display technology. Some of these areas of development are considered in more detail.

#### *Low-K-dielectrics (TRL 1 to TRL 2)*

To develop more powerful circuits, effort is being spent on equipping chips with new insulator materials. Low-K dielectrics are used as insulating media between the conducting wires. They enable higher switching speeds due to reduced capacitive loading and losses. Today's processors are based on insulating layers of conventional silicon oxide and have a dielectric of only 4. These insulating layers may not be arbitrarily reduced as the oxide loses its insulating properties below a certain thickness. One goal is to decrease this constant by half, and thus to speed up the chips by up to 40 %. Ideally a dielectric permittivity of 1 could be approached as it exists only in vacuum or in the air.

One approach being investigated is based on silica aerogels; they have a very low permittivity ( $1.1 < k < 2.5$ ) and are suitable due to their heat resistivity and the compatibility with semiconductor fabrication. Based on organic aerogels permittivities of 1.3 to 1.6 are achievable. The permittivity properties of aerogels may be varied with the pore volume (i. e. the density). A silica aerogel of a density of  $0.008 \text{ g/cm}^3$  resulted in a permittivity of 1.008, the lowest value ever measured with a solid.

#### *Aerogels as semiconductors (TRL 1 to TRL 2)*

Some aerogels, in particular those made of metal-chalcogenide composites open up application perspectives in the semiconductor industry. Aerogels made of cadmium selenide quantum dots have been fabricated in a three dimensional network. The researchers compared CdSe aerogels prepared from spherical and rod-shaped particles. Rod-shaped particles yielded aerogels with polymeric morphologies in contrast to the colloidal morphology obtained from spherical particles. Relative to the colloidal aerogels, the polymeric CdSe aerogels exhibited twice the surface area. Altering the shape of the building block from which nanostructured networks are assembled was an effective way to tune the basic properties of metal chalcogenide semiconducting aerogels.<sup>20</sup>

#### *Memory Devices/Displaytechnology (TRL 1 to TRL 2)*

Aerogels are suitable for the implantation of nanoparticles with specific properties. By that, the fabrication of magnetic aerogels may be achieved. Aerogels with magnetizable particles of compounds such as  $\text{Nd}_2\text{Fe}_{14}\text{B}$  result in a coercive magnetic material. Such hard magnets are suitable for opto-electronic applications. Aerogel based transparent magnets could serve as non volatile memory media or in flat panel displays in which the pixels are controlled magnetically.<sup>21</sup>

#### *Energy (TRL 5)*

Aerogels gained interest in energy storage applications. Due to their large internal surface aerogels are able to quickly incorporate electric charges or ions, to store them at small space and to release them quickly.

Conductive carbon aerogels have proved to be suitable for applications as electrode materials in supercapacitors, batteries and fuel cells. Such aerogels are promising for efficient spatially focused energy storage. With these properties they meet the needs of electric or hybride ve-

hicles that require not only high energy storage capacities but also specific properties such as fast charge release, to achieve acceptable vehicle acceleration. This is achievable by a combination of conventional batteries for permanent or uniform consumption, supercapacitors for high short term pulse power, or brake energy recuperation. At the electrolyte-aerosol interface within the supercapacitor a double layer builds up that stores large charge. The carbon electrodes used have extremely large surface areas of up to 2500 m<sup>2</sup>/g, resulting in specific capacitances of more than 100 F/g in organic and 250 F/g in aqueous electrolytes

Carbon aerogels are fabricated by pyrolysis of organic aerogels. The properties of the monolithic corpus may be arbitrarily varied by variations of the sol-gel-process and modifications of the pyrolysis parameters. The requirement of a large inner surface of the supercaps can be achieved by CO<sub>2</sub>-activation during pyrolysis at 900°C–1000°C.

By construction of planar electrodes, carbon aerogels may be efficiently integrated into small components such as button cell housings. The production of thin electrodes with thicknesses of up to 80 μm can be achieved through the integration of aerogels in fibrous tissue. The electrodes exhibited excellent mechanical strength and can be processed with simple cutting tools.

A number of scientific groups have been investigating the commercialisation. Meanwhile aerogel supercapacitors are mature products in the market and competing with conventional carbon electrodes.

Even in the development of rechargeable lithium batteries aerogels are being examined to increase electrode capacity. Conductive V<sub>2</sub>O<sub>5</sub>-MnO<sub>2</sub> aerogels, for example, show a 100% higher capacity compared to polycrystalline, non-porous powders.<sup>22</sup>

### *Environment (TRL 3)*

The environmental sector offers potential use of aerogels as electrode materials for capacitive de-ionization of water; for use in desalination of sea and brackish water. Other applications include the remediation of industrial and public wastewater as well as extraction in the medical and analytical sector.

Since carbon aerogels are characterized by an excellent chemical stability, they are suitable for robust use in water treatment and extraction.

Brackish water (salinity 800-3200 ppm) is conventionally purified by electro-dialysis or reverse osmosis. Electrochemical cleaning or capacitive de-ionisation using carbon aerogel electrodes achieves comparable results at a 10-20-fold lower power consumption.

Seawater remediation (32000 ppm salinity) based on carbon aerogels is as efficient as reverse osmosis. However, costly and wear sensitive membranes, needed for reverse osmosis, are not required.

Further applications in the environmental sector may be seen in the area of air purification (air filters) or waste water remediation. Aerogel composites are suitable to efficiently extract gaseous pollutants from air by adsorption. TiO<sub>2</sub>-impregnated aerogels are well suited to remove volatile organic compounds such as benzene from air by adsorption and subsequent photocatalytic cleavage. Hydrophobic aerogels can also be used in wastewater treatment for removal of organic solvents.

### *Adsorbants / additives / fillers (TRL 3)*

Quartz aerogels are non-toxic and good adsorbents for moisture, gases, and volatile organic components due to their high internal surface. This results in principle applicability as moisture-removing fillers in food, cosmetics, pharmaceuticals or packaging for moisture sensitive products for example. The integration of aerogels in textile fibres to absorb sweat and odours is also conceivable.

Due to their good rheological properties aerogels are furthermore used as flow agents utilised in various pharmaceutical products and as a filler and carrier in detergents toners and rubber. The flow properties of a powder are important in particular for drug formulation in the pharmaceutical industry. Aerogel materials can improve the flow properties of powders more effectively than conventional additives (such as Aerosil). Whether aerogels fillers may become an alternative to Aerosil is crucially dependent on establishing cost efficient manufacturing processes.

### *Sensors (TRL 3)*

Due to the large internal surface aerogels have application potential in bio-and chemo-sensors, since the active surface of the sensors and thus their sensitivity can be significantly increased. Furthermore sensitive molecules such as proteins and dyes may be immobilized in the porous gel matrix principally allowing for a simultaneous detection of a variety of analytes. The Sandia National Laboratories, for example, developed aerogel based biosensors for detection and defence of biological warfare agents as part of a DARPA research program. Requirements are aerogel materials with precisely controllable pore sizes for the selective inclusion of the analyte and the sensor components.

Aerogels are investigated as substrates, adsorbents, and chemical concentrators for new sensor applications (such as lab-on-a-chip systems).

Due to their transparency aerogels are also suitable for optical sensors. Optical oxygen sensors have been developed based silica aerogels at the Berkeley National Laboratory. Exposed to UV-light, the material showed a strong photo luminescence in the visible spectral range. The luminescence intensity was correlated to the oxygen concentration of the surrounding medium.

A fast response time, faster gas diffusion, and a better durability are additional advantages over conventional sensors. This results from the aerogel material not being sensitive to photo induced bleaching as is the case for organic dyes.

### *Medicine / agriculture (TRL 2)*

Due to their large internal surface aerogels offer good possibilities for utilisation of reservoirs for the diffusion-controlled release of substances as in pharmaceuticals, crop protection, hygiene and cosmetics. Because of the adjustability of pore size and distribution aerogels may be tailored; an example being the speed of drug release. Applications of aerogels as drug carriers in the pharmaceutical industry have been developed and patented since the mid-1990s in particular by the company Hoechst<sup>23</sup> and medicine or agriculture are potential application areas. Since silica aerogels have the same chemical composition as the physiologically acceptable Aerosil, pharmaceutical controlled-released applications within the human organism should, in principle, be possible. The loading of aerogels with drugs can be achieved by different methods

such as by dispersing aerogel in a drug solution or by loading of aerogels by adsorption of the drug from a solution in supercritical carbon dioxide. Studies showed an increased drug release for certain substances compared to conventional drug formulations. This could be useful especially for substances for which a rapid drug release is desirable.<sup>24, 25</sup>

Aerogel carriers could be an alternative to the conventional micronization of drugs to provide solubility. Applied in tablet production aerogels may serve both as drug carriers and to improve the flow properties.

The use of graded porous titanium oxide aerogel layers as a medical implant material has also been investigated. Due to the high density of hydroxyls within these aerogel layers, a good bio-functionalisation can be achieved through binding of biologically active substances.

#### *Lightweight construction materials (TRL 3)*

Due to their extremely low density there is a principal applicability of aerogels for lightweight purposes; however, the low mechanical stability remains a challenge. Much effort has been spent in appropriate improvements based on modifications with polymers or natural fibers like cellulose for example. Several potential applications have been cited for aerogels as construction material.

Scientists at the University of Oklahoma have developed an extremely lightweight but very hard aerogel material whose specific weight is only half as large as that of balsa wood. Unlike previous aerogels from silicates, metals or carbon, which are often quite fragile, this aerogel is much more resistant. It consists of cellulose fibers, which were cured with a method known from paper manufacturing. Only with the help of a hammer, is it possible to shatter a plate of the cellulose aerogel.<sup>26</sup> In addition to applications as a stable insulation material possible applications as a lightweight material include the automobile and the aerospace industries



Fig. 4: Aerogel material with improved mechanical properties<sup>27</sup> (Automobil Entwicklung)

Other silica aerogels could be used in automotive engineering, for example in new light bumpers, shock absorbers or other lightweight, but high-strength structures. Some aerogels consist of silicon nanoparticles and cross-networking polyurethane. At a density of about 0.44 g/cm<sup>3</sup> it weighs nearly six times less than aluminium, but has a structure more than a hundred times stronger than pure silica aerogel. The drying of the gel has already succeeded at atmospheric pressure. Thus essential prerequisites to commercial mass production are given.

### *Shock absorbers (TRL 2 to TRL 3)*

The brittleness of silica aerogels is a disadvantage for engineering and construction applications. However, exactly this property, the absorption of kinetic energy is promising for applications as shock absorbers. NASA have already made use of this for the collection of cosmic dust in the frame of their "Stardust mission". These micro-meteorites strike the aerogel matrix with the multiple speed of sound and are slowed and caught without major heat development.

However, even terrestrial purposes can make use of the excellent shock damping properties of aerogels in combination with their low weight. Applications such as cycle/motorbike helmets, as passenger protection in cars, or for damageable electronic devices is conceivable. Aerogels could compete here with conventional polymer foams.

### Current situation within the EU

In the aerogel sector, Europe is not in a leading position. The majority of research institutions are located in the USA and almost all aerogel related commercial activities are US-based companies (see Tab. 1).

This is also underlined by the patent situation. It is remarkable, that by far most of the patent applications are filed to the US Patent and Trademark Office (USPTO).

A formal search for the term "aerogel" within the patent applications at the World Intellectual Property Organisation (WIPO), which are assumed to be particularly valuable, reveals a fraction of 60 % of all applications being assigned to US-applicants followed by 7 % for Japan and 7 % for Germany. The latter, however, is in part due to the former activities of the German Hoechst AG, which has now been transferred to the US company Cabot Corp.

The EPO data, extracted from the free online patent service "esp@cenet" yield a slightly mitigated image with at least Germany being selected as priority country in almost a quarter of all applications. However, even in this view the US holds more than 40 % of the priorities and a considerable amount of the German priorities is again due to former Hoechst AG. Other European patent offices contribute only to a minor degree.

### Economic aspects

#### Market description

Aerogels can be characterised as materials with the lowest density of any known matter. According to their remarkable properties typical applications can be seen as thermal insulators, thickening agents in paints and cosmetics.

On the basis of their high electrical conductivity and stability they are of great interest as materials for electrodes used for fuel cells and super capacitors.

The focus of previous applications lies in the field of space sciences, whereas new fields of application could be seen in absorbing heavy metal pollutants like mercury, lead and cadmium from water and for drug delivery systems due to their biocompatibility. Dunlop for example introduced aerogels in their new tennis and squash racquets product line.

According to results of BCC Research the global market for aerogels accounted for \$82.9 million in 2008 and it is expected to reach \$646.3 million in 2013 with a compound annual growth rate (CAGR) of 50.8%. It is assumed that revenue growth for aerogels will be driven basically by thermal and acoustic insulation applications because currently this segment accounts for 70% of total aerogel revenues<sup>28</sup>. In comparison to that in 2006, the thermal insulation sector accounted for 57.6% of total revenues. So the assumption mentioned above seems to be well justified. 5 highlights the tendency in revenues for aerogels.

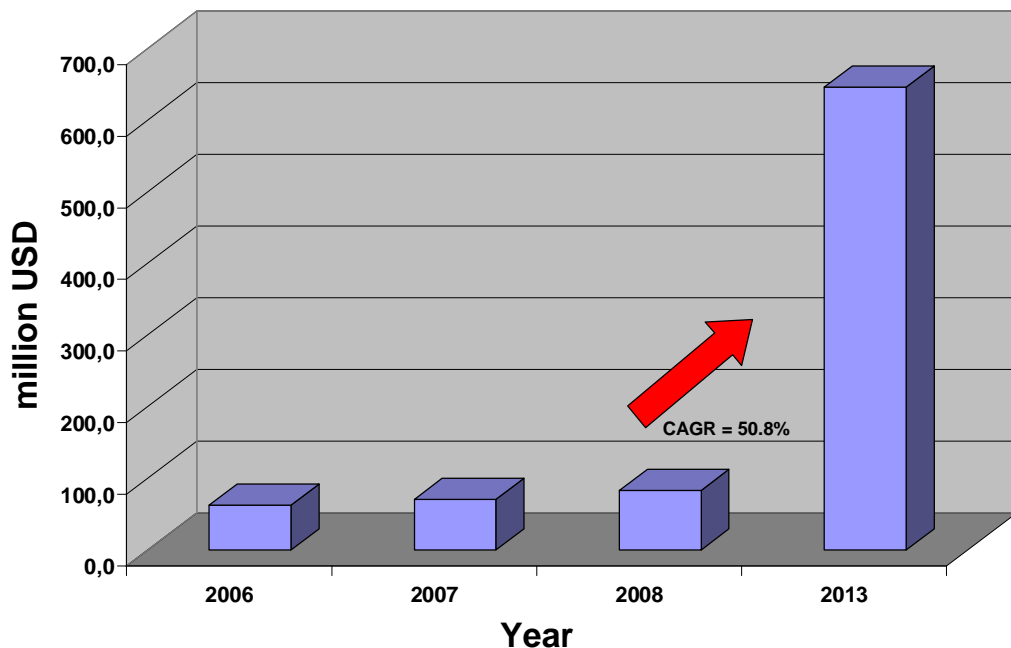


Fig. 5: Global revenues for aerogels in the years 2006 to 2013 (BCC Research)

Manufacturers of aerogels developed new types of aerogels and try to serve new commercial markets like textiles and fuel cells. As a result, it is forecasted that consumption will grow rapidly through 2011. The consumption will exceed 12,500 metric tons at an AAGR of 78.1%<sup>29</sup>.

As demonstrated above the market for aerogels is quite small and only a limited number of manufacturers play a role in this market segment (Tab. 1). Therefore, any changes in company's activities will have an impact on both manufacturing and sales distribution. Tab. 1 also demonstrates Europe's low importance in the sector of aerogels. Dunlop for example only distributes tennis and squash racquets.

The investigation of the patent situation underlines the weakness of the European market position. A first overview of the patent situation revealed that the number of patent applications applied at the US patent Office (USPTO) exceeds the number of EPO patent applications by a factor of more than 2.5. This may be seen as a first indicator for the significance of the European R&D situation. Analyses of WIPO data revealed similar results (see section "Current situation within the EU").

Tab. 2 shows the major industrial aerogel producers.

Company	Country
Aerogel Composite, LLC	USA
Aspen Aerogels, Inc.	USA
Cabot Corporation	USA
MarkeTech International, Inc.	USA
Taasi Aerogel Technologies	USA

Tab. 1: Key players in aerogel production<sup>30</sup>

Tab. 2 lists industrial segments for current or possible applications of aerogels. The table reveals that currently most of the aerogel applications can not be classified as consumer products.

Field of application	Possible use
Thermal and acoustic insulation	Pipelines
Electronics	Imaging systems, Semiconductor devices
Chemical/environmental	Catalysts and filters
Medical/biological/pharmaceutical/personal care	Biological carriers, Cosmetic additives
Sensors and instrumentation	Cherenkov detectors, media and parts for instrumentation
Energy	Fuel cells, supercaps
Aerospace and space exploration	Stardust detectors
Consumer	Jewellery, lamps, racquets
Defence	High temperature seals, military helmet trauma liners

Tab. 2: Current and future application areas for aerogels

### Nanotechnology impact

Aerogels are nanoporous materials. In comparison to conventional solid state materials they have a very high fraction of free volume. Due to the high pore volume and a low solid content low values of thermal conductivity can be expected.

Silica aerogels manufactured by sol-gel processing are known as insulation material with outstanding thermal properties.

According to their exceptional characteristics aerogels show unusual dielectric properties such as very low dielectric constants and high dielectric resistivities. At microwave frequencies they show very low dielectric losses.

#### Drivers and barriers to innovation

Aerogels possess a spectrum of interesting physical characteristics like low thermal conductivity, good mechanical properties, very light weight and the ability of high energy absorption. For these reasons aerogels are perfectly suited to insulation applications.

The most remarkable attribute of aerogel insulation is the respectable reduction of the amount of material needed to achieve the same thermal function.

Aerogels are one of the most efficient materials for insulation, although their high cost allows them to be applied only for specialised applications. Only the high energy costs have anticipated widespread applications. There are some applications in glazing and pipelines.

Aerogels can also be modified to provide durable water repellence. To eliminate or to reduce moisture from the insulation system helps to protect pipelines from corrosion.

The most important benefit employing aerogels in pipe insulation is an enhanced performance life that depends on its flexible blanket form and long-term water resistance. Furthermore, it is conceivable that energy savings could become realistic if it can be achieved to work at higher temperatures

Using aerogel-based technology should lead to lower installation costs, reduced hazardous emissions and reduced energy losses.

The main barriers for aerogels used for pipe insulation are high manufacturing costs especially when they require supercritical drying, high dust production during aerogel materials installations, lack of a complete OEM aerogel insulation, and a defined installation method.

Although nanotechnology cannot be described as a key technology for solar energy systems there are intentions to apply aerogels in order to develop transparent and isolating materials for solar collectors<sup>31</sup>.

Another promising example to employ aerogels in solar energy systems is the application of monolithic silica aerogel as an insulation material with transparent characteristics in glazings for windows<sup>32</sup>. In this connection an aerogel tile is inserted between two glass panes and the whole unit is sealed at the rim.

The main barrier in relation to the general application in windows, is the optical quality of the vision through the material; although numerous improvements have been made the same level of quality as ordinary glass panes could not be achieved.

#### Relevant product segments and applications

Nanotechnology is widely regarded as one of the twenty-first century's key technologies, and its economic importance is sharply on the rise. Potential fields of application for aerogels include:

- Thermal and acoustic insulation materials for pipelines and in the energy sector for fuel cells, lithium ion batteries and super capacitors;
- In space science, e. g. stardust detectors;
- Future applications can be seen in drug delivery systems due to their biocompatibility.
- Possible energy environmental applications can be identified in the cases filters and catalysts.
- Military applications include foam components produced for high-temperature seals and gaskets, aircraft seating and armrest pads, ejector-seat head-cushion pads, military helmet trauma liners, missile cushion packaging, night vision pouch foams, and ammunition box foams. Aerogel blankets can also be applied to reduce radically infrared emissions from, for example helicopters. This makes it much harder for heat-seeking missiles to lock on to them.
- Tennis along with golf, bowling, biking and skiing are sports where nanotechnology has an impact. Since the 1950s, the face of tennis has changed drastically with the introduction of the first commercially non-wood racket<sup>33</sup>. Wooden tennis rackets were much heavier and made it harder to accelerate the ball.
- In the meantime tennis companies produced rackets with aluminium, graphite or titanium. Wilson and Babolat, two tennis companies, produced rackets that incorporate carbon nanotubes. Another improvement is the employment of aerogel in order to influence the strength to weight ratio.

### Short application description

Due to their thermal conductivity characteristics there are many military and aerospace applications. Products made out of aerogels are employed as a thermal protection to avoid overheating and to achieve infrared suppression around hot components. Aerogel blanket material seems to be ideal for reduction of the thermal signature of hot structure. Another advantage is the minimal weight impact. The blankets can be attached for example to the inside of the engine cowling of a helicopter. The suppression of the infrared signature may help to prevent detection of the helicopter through hostile forces and makes it much harder for heat-seeking missiles to lock on to it.

Armed forces can utilise the structural strength of aerogel as armour for military vehicles; the material has shown its efficiency in the case of a direct dynamite blast. Other military applications are realised in light-weight jackets for armed forces personnel and bridges in defence use.

The essential objective of the Stardust mission is to collect cometary samples and interstellar dust. The main task is to accomplish the slowing down of the particles from their high velocity. In this context minimal heating or other effects that would cause their physical alteration are great challenges. Such particles, range in size from 100 nm to 10 µm and have velocities between 0.5 and 10 km/s. They can pass easily through gases but vaporise on impact with liquids or ordinary solids. Because aerogels show greater strength than air but are far less dense than regular solids, they have the capability to slow the dust particles gradually and capture them.

Another advantage is that aerogels preserve the tracks made by the particles. This can be used to isolate each particle for later investigations in the laboratory.

One of the first applications of aerogel materials was the insulation of pipelines in the oil and gas industry. Nowadays, aerogel insulated rollable pipe-in-pipe systems are state of the art. A typical pipe-in-pipe configuration consists of flow line, centraliser, insulations and carrier pipe-line. The main task of the centraliser is the protection of the integrity of the insulation material.

The main advantage of the reeling system is the onshore assembly of the pipe-in-pipe system. This allows a high welding quality and an integrity control of the entire pipe system.

During the offshore procedure stalks with a length of 500 m to 1000 m is tied-in by welding after the previous stalk is fully reeled<sup>34</sup>.

Very interesting consumer applications of aerogels include tennis and squash rackets which have been developed with the introduction of Aerogel 4D. 4D stands for four directional braiding and offers strength with extremely enhanced flexibility. Rackets using aerogel are 4 times more effective than those built up with carbon. Only one layer of 4D braiding is used compared to 4 layers of conventional carbon. The three-dimensional nanometre-sized molecular network achieves an enhanced strength to weight ratio for enhanced stiffness and a maximum of acceleration of the ball.

### Boundary conditions

Although aerogels exhibit outstanding characteristics and offer numerous potential applications commercialisation has been slow due to several factors.

Among these factors are high manufacturing costs for aerogels, industry requirements for insulation survivability temperature of 1200°F, and high dust production during aerogel installations.

According to information from the US Department of Energy a plan has been developed to attract the pipe insulation market. Aspen Aerogel has been successful in reducing of material costs and increased high-temperature durability<sup>35</sup>. This could help to broaden the market.

Up to now most of applications for aerogel materials were high-tech products and not consumer oriented. BCC states that in the case of tennis rackets the total consumption of advanced materials reaches a value of saturation. Currently, the exception is nanomaterials. An annual average growth rate of 208% is expected over the period 2005 to 2010<sup>36</sup>. Boundaries could be overcome through opening the markets for more consumer products.

### Product examples

#### *Nanogel*<sup>®</sup>

Nanogel<sup>®</sup> is the trade name for Cabot Corporation's silica aerogel products. The company manufactures aerogel since 2003 at its plant in Frankfurt, Germany. Cabot is the only company that developed a commercialised process that is able to achieve continuous production of the material under ambient conditions. Furthermore, the process provides control of the mate-

rial's porosity, pore size and pore distribution. Moreover, it is possible to bypass the traditional method of super-critical drying which is very expensive. That means that Nanogel<sup>®</sup> can be continuously manufactured in a cheaper way than others can do.

To the most interesting fields of application belong oil and gas pipelines, building insulation, personal care products, coatings and outdoor gear and apparel.

Fig. 6 shows Nanogel pellets for applications in the building and construction sector.

Nanogel is already used in window, roof, and facades glazing products of leading enterprises of the building industry like OKALUX GmbH in Marktheidenfeld, Germany. It shows an enduring hydrophobic behaviour that enhances the persistency against mould and therefore it contributes to the enhancement of lifetime.

Moreover, Nanogel opens new application fields because the architect has a greater margin to experience with daylighting of nanogel filled systems while the overall heat-transfer coefficient of material meets the criteria of the strong building code.



Fig.6: Nanogel<sup>®</sup> pellets from Cabot Corporation (Cabot Corp.; source: [www.bauarchiv.de](http://www.bauarchiv.de))

#### *Reelable Pipe-in-pipe System (PiP)*

Aerogel insulated reelable pipe-in-pipe assemblies are systems for sub sea applications of the gas and oil industry. This technology integrates into rigid pipe solutions. The system provides the level of insulation installation and the level of flow assurance needed for cost effective manufacturing in deep and ultra-deep water. The main components are carrier pipe, insulation, centraliser and flow pipe.

Fig. shows a typical reelable pipe-in-pipe configuration of Technip.

In addition to a low overall heat transfer coefficient an advantage which justifies the employment of aerogel insulation is the fact that aerogel can lead to a drop in the outer diameter of the carrier pipe. This can open economical and design perspectives. This can be very interesting in remote deepwater fields. Costs can be positively influenced by savings related to a

smaller outer pipeline and centralisers. Moreover, costs can be reduced on the due to a decrease of the welding costs of smaller carrier pipeline outer diameter.

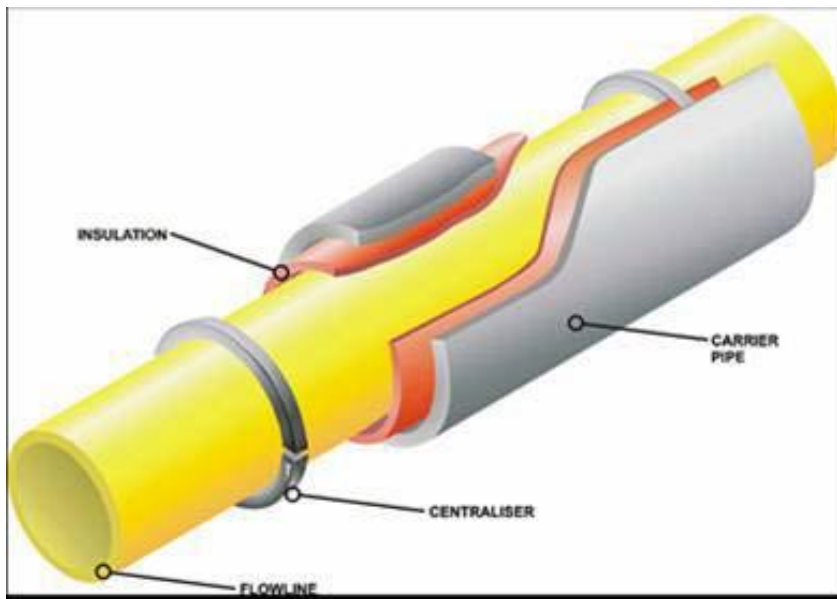


Fig. 7: Reelable pipe-in-pipe configuration (©Technip Coflexip Group)

#### *Dunlop Aerogel™ rackets*

Dunlop Sport offers a series of aerogel incorporating tennis rackets. They belong to the new Aerogel 4D Range which consists of the rackets 4D 2Hundred, 4D 3Hundred, up to 4D 9Hundred and Super-Lite. These are 100% graphite rackets with AEROGEL™ combined with the new 4D BRAIDED™ technology. D BRAIDED technology has been used at defined locations which improves the stability of the racket without affecting racket weight. 4D BRAIDED technology employs aerogel by integrating four directional braided super light S-glass fibres into the racket frame. One layer of 4D is capable to do the task of 4 layers of a traditional racket lay-up. The technology is able to minimise torsional twist of the frame caused for example by off-centre impacts of the frame.



Fig. 8: Dunlop Sport racket with aerogel and D Braided technology (Source: Dunlop Sport)

Dunlop AEROGEL™ rackets consist of the lightest solid, which has strength of up to 4,000 times its weight. The outstanding strength to weight ratio which is responsible for enhanced stiffness and increased power is due to three-dimensional nanometre-sized molecular network.

Economic information for present products

#### *Nanogel®*

Cabot Corporation belongs to the leading five manufacturers of aerogel raw material. For the fiscal year 2008 Cabot announced increased revenues for aerogel. The revenues increased in comparison to 2007. This financial success was driven by the construction, oil and gas market segments<sup>37</sup>. Due to the fact that the company secured orders in the key segment for aerogels Cabot expects revenue growth for the ongoing year 2009.

In 2007 the company gained revenues of \$3 million with aerogels within their new business segment of inkjet colorants and superior MicroPowders. One year later, they could record \$10 million.

Comparing the three and nine month periods of 2008 with equivalent periods in 2009 (the business year 2008 started in October 2007 and ended in September 2008) one can state that the revenues of the three months period 2008 are equal to the same period in 2009 namely \$2 million. For the nine month period which ended on the 30<sup>th</sup> of June one can observe an increase of about 220% in 2009. Total revenues for the nine months period 2009 are \$11 million.

These results show no indication that the recession had any negative influence on the current revenues in the aerogel market segment of the Cabot Corporation. This is in good agreement with results of the Lux Research report "The Recession's Ripple Effect on Nanotech"<sup>38</sup>. Among all nanomaterials, nanomaterials with a broad relation to the automotive and construction market will have a negative impact of the recession. Because Cabot' aerogels have no current applications in the automotive sector no negative impact from this segment needs to be expected. Up to now, the success of the company was also driven by the construction segment. Due to increasingly stringent energy-efficiency standards for buildings aerogels could be an interesting solution for architects because Cabot's Nanogel offers more insulation performance with less thickness. So, a negative impact on the company's revenues could be averted.

#### *Reelable Pipe-in-pipe system (PiP)*

Aerogel insulated reelable pipe-in-pipe assemblies are systems for sub sea applications. In Technip's annual reports activities concerning these systems are mentioned under the term SURF segment. SURF stands for Subsea Umbilicals Risers and Flowlines.

In 2007 the Technip Group gained revenues in the SURF segment of \$2,478.2 million with a growth rate of 12.2% compared to 2006<sup>39</sup>. Information from annual reports doesn't separate between revenues of aerogel projects and others so revenues of reelable pipe-in-pipe systems can only be estimated.

In 2007 Technip won contracts with the Brazilian enterprise Petrobras which are worth of approximately € 200 million. The Canapu pipeline is the first in Brazil with the use of a pipe-in-pipe design and aerogel as an insulation media<sup>40</sup>.

Assuming that the Brazilian project using aerogel was the only one in 2007 revenues would account for approximately 10% of the SURF market segment. In 2008 revenues in the sub sea segment accounted for €2,689.0 million. It is an increase of 8.5% over 2007. For 2009 a stable to moderate growth in the sub sea segment is expected<sup>41</sup>.

In relation to the recession the CEO of Technip, Mr. Thierry Pilenko explained that the recent decrease in energy demand in connection with uncertain commodity prices and thus falling project costs, is affecting the entire supply chain.

Moreover, he declares that projects which are in the procurement or construction phase continue to advance, but new projects or projects that are at an early stage are being deferred. Large scale projects are being re-evaluated in order to take advantage of the lower costs. The observed tough decision process is likely to continue until costs stabilise – but the time frame is difficult to forecast under the current economic conditions. Therefore, it can be asserted that the reactions of the customers depend on their balance sheets. Leveraged companies are reducing their investments while others with strong financial resources continue to invest.

It is anticipated that the current situation will give Technip opportunities to use its trumps. First, the company is well-diversified in relation to clients, activities and geography. Second, its vertical integration in the sub sea segment gives the company control of the supply chain and cost structure. Last but not least continuous investments in R&D are enabling the enterprise to develop cost effective and cutting-edge solutions. Moreover, Technip can refer to a track record of large project execution.

#### *Dunlop Aerogel™ rackets*

Sports industry is an important revenue generator in world economy but over the past two decades, racket sports have suffered a steady decline in participation rates and equipment sales<sup>42</sup>. But now, declines in the number of players and racket sales are expected to demonstrate improvement within this decade.

Due to the lack of direct information about revenues of Dunlop Sport estimations have to be provided.

To the top five tennis companies belong Wilson, Head, Prince Sports Group, Prokennex and Dunlop Sports. The five companies generate about 85 percent of the total world output whereas Wilson and Head share 61% of the entire market. In 2006 the entire market was worth of \$428 million. Wilson is the undisputed market leader with 36%. In 2006 the company produced 3.4 million rackets representing \$151 million. Prince Sports Group, Prokennex and Dunlop Sports share 24% of the total market. Under the condition that each company shares 8%, revenues for Dunlop Sports account for \$34 million. Supposing that 80% of Dunlop's revenues come from its aerogel products the company earned around \$27.2 million in 2006.

Although production numbers for tennis rackets are slowly increasing, competition is driving costs down. As a result, nearly all tennis rackets are manufactured in China. This trend is well established and will continue.

An economic recession does not bode well for any leisure-products market and especially for the tennis racket market because in times of economical crisis consumers concentrate on basics of existence for their daily life. Dunlop has to fight against the impact of the economic crisis but also against his competitor, the Prince Sports Group. In January 2009, Prince an-

nounced the introduction of EXO3, its newest tennis racket line, endowed with a completely new frame. With this new concept it is possible to transfer up to 26% more energy back into the tennis ball upon contact. This effect can be realised by a conventional manufacturing process. Now, Dunlop's nanotechnology products have to compete with Prince' conventional racket. Time will show which product will become accepted in the market.

#### Profiles of selected key companies

##### *Cabot Corporation*

Cabot Corporation is a worldwide acting materials company that was founded in 1882. It has its headquarters in Boston, Massachusetts. Furthermore, their regional headquarters are located in Alpharetta, Georgia, Shanghai, China and Leuven, Belgium. The company has 39 manufacturing units with locations in the USA and 19 other countries. Cabot Corporation possesses 8 research and development facilities and 28 sales offices. Currently, the company has 4,200 employees<sup>43</sup>.

Cabot developed a new business strategy engaging small companies through its Fine Particle Network (FPN). The idea of the FPN is the fact that smaller companies often make a profit by cooperation with a larger partner that can convince other partners to work with them.

As a service in return Cabot makes a profit by having access to external technologies. Cabot's intention is to achieve that partners will have access to particle technology solutions no matter whose invention it is.

For the fiscal year 2008 Cabot Corporation can point to sales revenues of \$3.2 billion.

To the product line of the company belong rubber and specialty grade carbon blacks, inkjet colorants, fumed metal oxides, aerogel, tantalum and caesium drilling fluids among others. The fields of application for their products vary from aerospace and defence over construction to life science.

##### *Technip Coflexip Group*

Technip Group has its headquarters in Courbevoie, France. The company is responsible for sub-sea and deepwater solutions to the offshore oil and gas industry.

Technip has about 23,000 employees in 46 countries and their operating income accounts for €657 million. In 2008 the total revenues amount ed to €7.5 billion.

Technip offers services ranging from basic and detail engineering, procurement, construction, and project management at optimized costs. The Group has vast experience in implementing large turnkey contracts and arranging related international financing on behalf of its clients. Especially in the offshore segment, Technip can fulfil the expectations of operators that want to entrust the largest possible range of services to a sole contractor able to manage all aspects of a major field development.

Referring to over 50 years of experience the enterprise acts in three segments of the oil and gas market: sub-sea, offshore, and onshore. It supplies a large range of deepwater production facilities and provides technical expertise in moorings, pipeline-riser-umbilical systems and robotics.

In the sub sea segment, Technip develops equipment which is able to withstand the extreme pressure and temperature conditions of hydrocarbon fields at water depths greater than 3,000 metres.

In the offshore segment, the enterprise develops methods for platform installations to reduce installation time and cost. Furthermore, they design new platform models suitable for the exploitation of hydrocarbon fields under extreme conditions such as the climate in the Arctic Ocean.

In the onshore segment, research and development have enabled the group to extend mega-sized LNG complexes, to upgrade and to refine non-conventional resources, and to improve the environmental performance of their industrial installations.

In March 2009 Technip received a completed Space loft advanced thermal insulation for a 21-km sub-sea natural gas pipeline from Aspen Aerogels. This pipeline connects Petrobras's Canapu field in a depth of 1,700 m to its production platform Cidade de Vitoria in 1,400 m water depth. Technip installed the aerogel insulation on the pipes at its spool base in Mobile, Ala., before the freight has been carried to Brazil.

#### *Dunlop Sport*

Dunlop Tyres were established in 1886. Ten years after the production of the first Dunlop tennis racket the Dunlop Sports Company was formed in 1928. Four years later the company introduced their product line Maxply which should become the most famous rackets for the following fifty years. The German tennis player Gottfried von Cramm was the first finalist in Wimbledon to play with a Dunlop Maxply racket. In 1979 the company started production of rackets with a frame made of graphite at their German plant in Erbach.

In 1959 Dunlop purchased the family business of Ralph Slazenger and formed Dunlop Slazenger. Slazenger was an old and famous British sports equipment brand name.

In 1985 BTR plc bought Dunlop Slazenger and sold the Division in 1996. Now, Dunlop Sport is owned by the British company Sports World International, known as Sports Direct International plc, who purchased the firm from CINVen in 2004 for £40 million.

Dunlop Sports has its headquarters in Greenville South Carolina and up to 200 employees. In 2007 Dunlop Sports introduced the Aerogel racket technology.

## References and Literature

---

- <sup>1</sup> R.W. Pekala : Organic aerogels from the polycondensation of resorcinol with formaldehyde, in Journal of Material Science, Vol. 24, pp. 3221-3227, 1989
- <sup>2</sup> C. Tan, B. M. Fung, J. K. Newman, C. Vu: "Organic Aerogels with Very High Impact Strength", Advanced Materials, Volume 13, Issue 9, 2001, pp 644-646; <http://www.ou.edu>
- <sup>3</sup> [http://www.ep2.physik.uni-wuerzburg.de/ag\\_fricke/graphic/start\\_js.htm](http://www.ep2.physik.uni-wuerzburg.de/ag_fricke/graphic/start_js.htm)
- <sup>4</sup> N. Leventis et al.: "Nanoengineering Strong Silica Aerogels", Nano Letters Vol. 2, No. 9, 11. 09.2002, pp. 957 – 960
- <sup>5</sup> J. Moon-ho, et al. (1997): "SiO<sub>2</sub> aerogel films as a novel intermetal dielectric", J. Appl. Phys. 82 (3) 1997, p 1299
- <sup>6</sup> U. Janosovits, G. Ziegler, U. Scharf, A. Wokaun, J. Non-Cryst. Solids, 210 (1997) 1
- <sup>7</sup> D. J. Suh, T.-J. Park, Chem. Mater, 8 (1996) 509
- <sup>8</sup> L. L. Hench, J. K. West, Chem. Rev. 1990, **90**, 33; L. L. Hench, Am. Ceram. Soc. Bull. **47** (1998) 67
- <sup>9</sup> S. S. Kistler, Nature 1931, 127, 741; J. Phys. Chem. 1932, **36**, 52
- <sup>10</sup> S. J. Teichner, G. A. Nicolaon, M. A. Vicarini, G. E. E. Gardes, Adv. Colloid Interface Sci. 5 (1976) 245
- <sup>11</sup> A. Hunt, M. Ayers, W. Cao, J. of Non-Cryst. Solids 185, 1995, 227; A. Hunt, J. Non-Cryst.Solids 225, 1998, 303
- <sup>12</sup> L. L. Hench, J. K. West, Chem. Rev. 1990, **90**, 33; L. L. Hench, Am. Ceram. Soc. Bull. **47** (1998) 67
- <sup>13</sup> N. Hüsing, U. Schubert, Angew. Chem., **110** (1998) 22; Angew. Chem. Int. Ed., **37** (1998) 22-45
- <sup>14</sup> <http://www.gizmowatch.com/entry/aerogel-a-miracle-material-to-transform-the-21st-century/>
- <sup>15</sup> Project: „Highly insulating and light transmitting aerogel glazing for window“ Laufzeit bis 11/2001 (Quelle: [www.dbs.cordis.lu](http://www.dbs.cordis.lu))
- <sup>16</sup> <http://www.glacierbay.com/Insulation.htm>

- 
- <sup>17</sup> NASA 1998: NASA Success Story: Aspen Aerogel Technology (<http://technology.ksc.nasa.gov/WWWaccess/Stories/AerogelRevisedSS.pdf>)
- <sup>18</sup> [http://eelndom1.ee.doe.gov/oit/oitpdf.nsf/Files/lbnl\\_composites.pdf/\\$file/lbnl\\_composites.pdf](http://eelndom1.ee.doe.gov/oit/oitpdf.nsf/Files/lbnl_composites.pdf/$file/lbnl_composites.pdf)
- <sup>19</sup> Patent: "High Yield Vapor Phase Deposition Method For Large Scale Single Walled Carbon Nanotube Preparation", Veröffentlichungsnummer WO2001049599A2
- <sup>20</sup> H. Yu, R. Bellair, R.M. Kannan, S. Brock (2008). "Engineering Strength, Porosity, and Emission Intensity of Nanostructured CdSe Networks By Altering The Building Block Shape". *Journal of the American Chemical Society* 130 (15): 5054–5055
- <sup>21</sup> M. Gich, et al., Applied Physics Letters, 82, 4307 - 4309, (2003)
- <sup>22</sup> W. Dong, J. Sakamoto and B. Dunn, "Electrochemical Properties of Vanadium Oxide Aerogels and Aerogel Nanocomposites", *J. Sol-Gel Science and Technol.* 26, 641 (2003); <http://www.seas.ucla.edu/ms/faculty1/dunn.html>; [http://www1.cems.umn.edu/research/crc/NanoComposite\\_Momma.html](http://www1.cems.umn.edu/research/crc/NanoComposite_Momma.html)
- <sup>23</sup> Patent "Use of inorganic aerogels in pharmacy", 1995 [DE]19506141
- <sup>24</sup> Günther, U., Smirnova, I., Neubert, R.H.H.; Hydrophilic silica aerogels as dermal drug delivery systems - dithranol as a model drug; *European Journal of Pharmaceutics and Biopharmaceutics*, 69 (3), (2008), 935-942
- <sup>25</sup> Smirnova, I., Suttiruwong, S., Arlt, W.; Aerogels: tailor-made carriers for immediate and prolonged drug release; *KONA*, 23, (2005), 86-97
- <sup>26</sup> *Advanced Materials*", Bd. 13, S. 644
- <sup>27</sup> <http://www.automobil-produktion.de/imperia/md/content/ap/heftausgaben/leseprobe/24.pdf>
- <sup>28</sup> *Advanced Materials, Aerogels*, BCC Research Report Code: AVM052B, 2009
- <sup>29</sup> *Advanced Materials, Aerogels*, BCC Research Report Code: AVM052A, 2006
- <sup>30</sup> <http://www.chemlin.de/markt/aero>
- <sup>30</sup> [http://paccs.fugadeideas.org/aerogel\\_gel.htm](http://paccs.fugadeideas.org/aerogel_gel.htm)
- <sup>31</sup> [www.solar-na-klar.de](http://www.solar-na-klar.de)

---

<sup>32</sup> <http://paccs.fugadeideas.org/aerogel/aerogel.shtml>

<sup>33</sup> <http://www.itftennis.com/technical/equipment/rackets/history.asp>

<sup>34</sup> <http://www.aerogel.com/markets/PDF/otc.pdf>

<sup>35</sup> <http://www1.eere.energy.gov/industry/imf/pdfs/aerogel.pdf>

<sup>36</sup> <http://www.bccresearch.com/report/AVM053A.html>

<sup>37</sup> <http://investor.cabot-corp.com/phoenix.zhtml?c=94559&p=irol-newsArticle&id=1219459>

<sup>38</sup> [http://www.nanotech-now.com/news.cgi?story\\_id=33648](http://www.nanotech-now.com/news.cgi?story_id=33648)

<sup>39</sup> [http://www.technip.com/english/pdf/Technip\\_RE\\_2007\\_en.pdf](http://www.technip.com/english/pdf/Technip_RE_2007_en.pdf)

<sup>40</sup> [http://www.ogj.com/index/article-display.articles.oil-gas-journal.volume-107.Issue\\_24.Transportation.Subsea\\_pipeline\\_developments\\_advance\\_operations\\_\\_integrity.QP129867.dcmp=rss.page=1](http://www.ogj.com/index/article-display.articles.oil-gas-journal.volume-107.Issue_24.Transportation.Subsea_pipeline_developments_advance_operations__integrity.QP129867.dcmp=rss.page=1)

<sup>41</sup> <http://www.reuters.com/article/pressRelease/idUS66076+19-Feb-2009+BW20090219>

<sup>42</sup> <http://www.compositesworld.com/articles/market-outlook-carbon-fiber-in-sporting-goods.aspx>

<sup>43</sup> <http://investor.cabot-corp.com/phoenix.zhtml?c=94559&p=irol-IRHome>

### Expert Acknowledgement

The authors would like to thank a number of experts for kind support and engagement and for critically reviewing draft versions of the report:

Mrs. Dr. A. Crossley (University of Oxford, UK)

Prof. Dr. A. Dommann (Centre Suisse d'Electronique et de Microtechnique (CSEM), Switzerland)

Prof. Dr. H.-J. Fecht (University of Ulm, Germany)

Dr. P. Gluche (Diamaze, Switzerland)

Dr. C. Johnston (Faraday Society, UK)

Dr. A. Leson (Fraunhofer-Institut für Werkstoff- und Strahltechnik (IWS), Dresden, Germany)