

Dry Tech Aerogel Technology

Aerogel



A block of aerogel in a person's hand

Aerogel is a [synthetic](#) porous [ultralight material](#) derived from a [gel](#), in which the [liquid](#) component of the gel has been replaced with a [gas](#). The result is a solid with extremely low [density](#)¹ and low [thermal conductivity](#). Nicknames include *frozen smoke*, *solid smoke*, *solid air*, or *blue smoke* owing to its [translucent](#) nature and the way [light scatters](#) in the material. It feels like fragile [expanded polystyrene](#) to the touch. Aerogels can be made from a variety of chemical compounds.

Aerogel was first created by [Samuel Stephens Kistler](#) in 1931, as a result of a bet with Charles Learned over who could replace the liquid in "jellies" with gas without causing shrinkage.

Aerogels are produced by extracting the liquid component of a gel through [supercritical drying](#). This allows the liquid to be slowly dried off without causing the solid matrix in the gel to collapse from [capillary action](#), as would happen with conventional [evaporation](#). The first aerogels were produced from [silica gels](#). Kistler's later work involved aerogels based on [alumina](#), [chromia](#) and [tin dioxide](#). [Carbon](#) aerogels were first developed in the late 1980s.

Aerogel does not have a designated material with set chemical formula but the term is used to group all the material with a certain geometric structure.

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Properties



A flower is on a piece of aerogel which is suspended over a flame from a [Bunsen burner](#). Aerogel has excellent insulating properties, and the flower is protected from the flame.

Despite their name, aerogels are solid, rigid, and dry materials that do not resemble a gel in their physical properties: the name comes from the fact that they are made *from* gels. Pressing softly on an aerogel typically does not leave even a minor mark; pressing more firmly will leave a permanent depression. Pressing extremely firmly will cause a catastrophic breakdown in the sparse structure, causing it to shatter like glass – a property known as [friability](#); although more modern variations do not suffer from this. Despite the fact that it is prone to shattering, it is very strong structurally. Its impressive load bearing abilities are due to the [dendritic](#) microstructure, in which [spherical](#) particles of average size (2–5 [nm](#)) are fused together into clusters. These clusters form a three-dimensional highly [porous](#) structure of almost [fractal](#) chains, with pores just under 100 nm. The average size and density of the pores can be controlled during the manufacturing process.

Aerogel is a material that is 98.2% air. Aerogel has a porous solid network that contains air pockets, with the air pockets taking up the majority of space within the material. The lack of solid material allows aerogel to be almost weightless.

Aerogels are good [thermal insulators](#) because they almost nullify two of the three methods of [heat transfer](#) (convection, conduction, and radiation). They are good [conductive](#) insulators because they are composed almost entirely of gases, which are very poor heat conductors. (Silica aerogel is an especially good insulator because silica is also a poor conductor of heat; a metallic or carbon aerogel, on the other hand, would be less effective.) They are good [convective](#) inhibitors because air cannot circulate through the lattice. Aerogels are poor [radiative](#) insulators because infrared radiation (which transfers heat) passes through them.

Owing to its [hygroscopic](#) nature, aerogel feels dry and acts as a strong [desiccant](#). People handling aerogel for extended periods should wear gloves to prevent the appearance of dry brittle spots on their skin.

The slight color it does have is due to [Rayleigh scattering](#) of the shorter [wavelengths](#) of [visible light](#) by the nano-sized dendritic structure. This causes it to appear smoky blue against dark backgrounds and yellowish against bright backgrounds.

Aerogels by themselves are [hydrophilic](#), but chemical treatment can make them [hydrophobic](#). If they absorb moisture they usually suffer a structural change, such as contraction, and deteriorate, but degradation can be prevented by making them hydrophobic. Aerogels with hydrophobic interiors are less susceptible to degradation than aerogels with only an outer hydrophobic layer, even if a crack penetrates the surface. Hydrophobic treatment facilitates processing because it allows the use of a [water jet cutter](#).

Knudsen effect

Aerogels may have a [thermal conductivity](#) smaller than that of the gas they contain. This is caused by the [Knudsen effect](#), a reduction of thermal conductivity in gases when the size of the cavity encompassing the gas becomes comparable to the [mean free path](#). Effectively, the cavity restricts the movement of the gas particles, decreasing the thermal conductivity in addition to eliminating convection. For example, thermal conductivity of air is about 25 mW/m,K at STP and in a large container, but decreases to about 5 mW/m,K in a pore 30 nanometers in diameter.

Structures

Aerogel structure results from a [sol-gel polymerization](#), which is when [monomers](#) (simple molecules) react with other monomers to form a sol or a substance that consists of bonded, cross-linked [macromolecules](#) with deposits of liquid solution between them. When the material is critically heated the liquid is [evaporated](#) out and the bonded, [cross-linked](#) macromolecule frame is left behind. The result of the polymerization and critical heating is the creation of a material that has a porous strong structure classified as aerogel. Variations in synthesis can alter the surface area and pore size of the aerogel. The smaller the pore size the more susceptible the aerogel is to fracture.

Waterproofing

Aerogel contains particles that are 2–5 nm in diameter. After the process of creating aerogel, it will contain a large amount of hydroxyl groups on the surface. The [hydroxyl groups](#) can cause a strong reaction when placing it in water. The aerogel will catastrophically dissolve in the water. One way to waterproof the [hydrophilic](#) aerogel is by soaking the aerogel with some chemical base that will replace hydroxyl groups with non-polar groups on the surface, the non-polar groups (-OR) is most effective when R is an [aliphatic](#) group.

Porosity of aerogel

There are several ways to determine the porosity of aerogel: the three main methods are gas [adsorption](#), mercury porosimetry, and scattering method. In gas adsorption, nitrogen at its boiling point is adsorbed into the aerogel sample. The gas being adsorbed is dependent on the size of the pores within the sample and on the partial pressure of the gas relative to its [saturation pressure](#). The volume of the gas adsorbed is measured by using the Brunauer, Emmet and Teller formula ([BET](#)), which gives the specific [surface area](#) of the sample. At high partial pressure in the adsorption/desorption the Kelvin equation gives the pore size distribution of the sample. In mercury porosimetry, the [mercury](#) is forced into the aerogel porous system to determine the pores' size, but this method is highly inefficient since the solid frame of aerogel will collapse from the high compressive force. The scattering method involves the angle-dependent deflection of radiation within the aerogel sample. The sample can be solid particles or pores. The radiation goes into the material and determines the fractal geometry of the aerogel pore network. The best radiation wavelengths to use are X-rays and neutrons. Aerogel is also an open porous network: the difference between an open porous network and a closed porous network is that in the open network, gases can enter and leave the substance without any limitation, while a closed porous network traps the gases within the material forcing them to stay within the pores. The high porosity and surface area of silica aerogels allow them to be used in a variety of environmental filtration applications.

Materials



A 2.5 kg [brick](#) is supported by a piece of aerogel with a mass of 2 g.

Silica

Silica aerogel is the most common type of aerogel, and the most extensively studied and used. It is [silica](#)-based and can be derived from [silica gel](#) or by a modified [Stöber process](#). The lowest-density silica Nano foam weighs $1,000 \text{ g/m}^3$, which is the evacuated version of the record-aerogel of $1,900 \text{ g/m}^3$. The density of [air](#) is $1,200 \text{ g/m}^3$ (at 20°C and 1atm). As of 2013, [aero graphene](#) had a lower density at 160 g/m^3 , or 13% the density of air at room temperature.

The silica solidifies into three-dimensional, intertwined clusters that comprise only 3% of the volume. Conduction through the solid is therefore very low. The remaining 97% of the volume is composed of air in extremely small nano pores. The air has little room to move, inhibiting both convection and gas-phase conduction.

Silica aerogels also have a high optical transmission of $\sim 99\%$ and a low refractive index of ~ 1.05 .

It has remarkable thermal isolative properties, having an extremely low [thermal conductivity](#): from 0.03 W/(m,K) in atmospheric pressure down to 0.004 W/(m,K) in modest vacuum, which correspond to [R-values](#) of 14 to 105 (US customary) or 3.0 to 22.2 (metric) for 3.5 in (89 mm) thickness. For comparison, typical wall insulation is 13 (US customary) or 2.7 (metric) for the same thickness. Its [melting point](#) is 1,473 K ($1,200^\circ\text{C}$; $2,192^\circ\text{F}$).

Until 2011, silica aerogel held 15 entries in [Guinness World Records](#) for material properties, including best insulator and lowest-density solid, though it was ousted from the latter title by the even lighter materials [aero graphite](#) in 2012^[23] and then [aero graphene](#) in 2013.

Carbon

[Carbon](#) aerogels are composed of particles with sizes in the [nanometer](#) range, [covalently bonded](#) together. They have very high [porosity](#) (over 50%, with pore diameter under 100 nm) and surface areas ranging between $400\text{--}1,000 \text{ m}^2/\text{g}$. They are often manufactured as composite paper: non-woven paper made of [carbon fibers](#), impregnated with [resorcinol–formaldehyde](#) aerogel, and [pyrolyzed](#). Depending on the density, carbon aerogels may be electrically conductive, making composite aerogel paper useful for electrodes in [capacitors](#) or deionization electrodes. Due to their extremely high surface area, carbon aerogels are used to create [supercapacitors](#), with values ranging up to thousands of [farads](#) based on a capacitance density of 104 F/g and 77 F/cm^3 . Carbon aerogels are also extremely "black" in the infrared spectrum, reflecting only 0.3% of radiation between 250 nm and $14.3 \text{ }\mu\text{m}$, making them efficient for [solar energy](#) collectors.

The term "aerogel" to describe airy masses of [carbon nanotubes](#) produced through certain [chemical vapor deposition](#) techniques is incorrect. Such materials can be spun into fibers with strength greater than [Kevlar](#), and unique electrical properties. These materials are not aerogels, however, since they do not have a monolithic internal structure and do not have the regular pore structure characteristic of aerogels.

Metal oxide

[Metal oxide](#) aerogels are used as catalysts in various chemical reactions/transformations or as precursors for other materials.

Aerogels made with [aluminium oxide](#) are known as alumina aerogels. These aerogels are used as catalysts, especially when "doped" with a metal other than aluminium. [Nickel](#)-alumina aerogel is the most common combination. Alumina aerogels are also being considered by [NASA](#) for capturing hypervelocity particles; a formulation doped with [gadolinium](#) and [terbium](#) could [fluoresce](#) at the particle impact site, with the amount of fluorescence dependent on impact energy.

One of the most notable differences between silica aerogels and metal oxide aerogel is that metal oxide aerogels are often variedly colored.

Aerogel	Colour
Silica, alumina, titania, zirconia	Clear with Rayleigh scattering blue or white
Iron oxide	Rust red or yellow, opaque
Chromia	Deep green or deep blue, opaque
Vanadium	Olive green, opaque
Neodymium oxide	Purple, transparent
Samarium oxide	Yellow, transparent
Holmium oxide, erbium oxide	Pink, transparent

Other

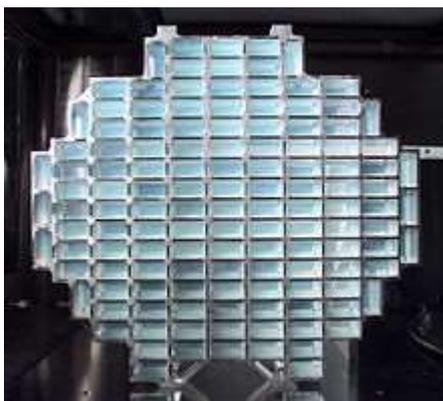
Organic polymers can be used to create aerogels. [SEA gel](#) is made of [agar](#). Cellulose from plants can be used to create a flexible aerogel.

[Chalcogel](#) is an aerogel made of [chalcogens](#) (the column of elements on the periodic table beginning with oxygen) such as sulfur, selenium and other elements. Metals less expensive than platinum have been used in its creation.

Aerogels made of [cadmium selenide quantum dots](#) in a porous 3-D network have been developed for use in the semiconductor industry.

Aerogel performance may be augmented for a specific application by the addition of [dopants](#), reinforcing structures and hybridizing compounds. Aspen Aerogels makes products such as Space loft which are composites of aerogel with some kind of fibrous batting.

Applications



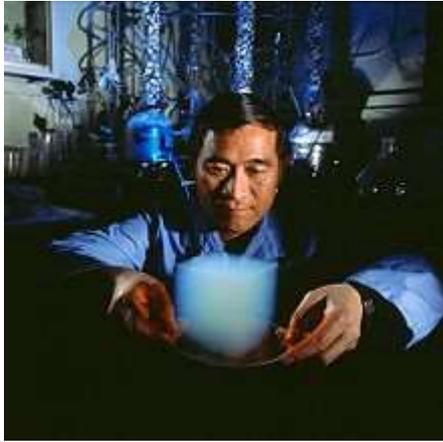
The [Stardust](#) dust collector with aerogel blocks. (NASA)

Aerogels are used for a variety of applications:

- In 2004 about US\$25 million of aerogel insulation product were sold, which had risen to about US\$500 million by 2013. This represents the most substantial economic impact of these materials today. The potential to replace conventional insulation by aerogel solutions in the building and construction sector as well as in industrial insulation is quite significant.
- In granular form to add [insulation](#) to [skylights](#). Georgia Institute of Technology's 2007 [Solar Decathlon](#) House project used an aerogel as an insulator in the semi-transparent roof.
- A chemical [absorber](#) for cleaning up spills.
- A [catalyst](#) or a catalyst carrier.
- Silica aerogels can be used in imaging devices, optics, and light guides.
- A material for filtration due to its high surface area and porosity, to be used for the removal of heavy metals
- [Thickening agents](#) in some [paints](#) and [cosmetics](#).
- As components in energy absorbers.
- Laser targets for the [National Ignition Facility](#).
- A material used in impedance matchers for transducers, speakers and range finders.
- Commercial manufacture of aerogel 'blankets' began around the year 2000, combining silica aerogel and fibrous reinforcement that turns the brittle aerogel into a durable, flexible material. The mechanical and thermal properties of the product may be varied based upon the choice of reinforcing fibers, the aerogel matrix and [opacification additives](#) included in the composite.
- [NASA](#) used an aerogel to trap [space dust](#) particles aboard the [Stardust](#) spacecraft. The particles vaporize on impact with solids and pass through gases, but can be trapped in aerogels. NASA also used aerogel for [thermal insulation](#) of the [Mars Rover](#) and [space suits](#).
- The [US Navy](#) is evaluating aerogel undergarments as passive thermal protection for divers.
- In [particle physics](#) as radiators in [Cherenkov effect](#) detectors, such as the ACC system of the Belle detector, used in the [Belle Experiment](#) at [KEKB](#). The suitability of aerogels is determined by their low [index of refraction](#), filling the gap between gases and liquids, and their transparency and solid state, making them easier to use than [cryogenic](#) liquids or compressed gases. Their low mass is also advantageous for space missions.
- [Resorcinol-formaldehyde](#) aerogels (polymers chemically similar to [phenol formaldehyde resins](#)) are used as precursors for manufacture of carbon aerogels, or when an organic insulator with large surface area is desired. They come as high-density material, with surface area about 600m²/g.
- Metal-aerogel [nanocomposites](#) prepared by impregnating the hydrogel with solution containing ions of a [transition metal](#) and irradiating the result with [gamma rays](#), precipitates nanoparticles of the metal. Such composites can be used as [catalysts](#), sensors, [electromagnetic shielding](#), and in waste disposal. A prospective use of platinum-on-carbon catalysts is in [fuel cells](#).
- As a drug delivery system owing to its [biocompatibility](#). Due to its high surface area and porous structure, drugs can be adsorbed from supercritical CO₂. The release rate of the drugs can be tailored by varying the properties of the aerogel.
- Carbon aerogels are used in the construction of small electrochemical double layer [supercapacitors](#). Due to the high surface area of the aerogel, these capacitors can be 1/2000th to 1/5000th the size of similarly rated electrolytic capacitors. Aerogel supercapacitors can have a very low [impedance](#) compared to normal supercapacitors and can absorb or produce very high peak currents. At present, such capacitors are [polarity-sensitive](#) and need to be wired in series to achieve a working voltage of greater than about 2.75 V.
- [Dunlop Sport](#) uses aerogel in some of its racquets for tennis, squash and badminton.
- In water purification, [chalcogels](#) have shown promise in absorbing the heavy metal pollutants mercury, lead, and cadmium from water.
- Aerogel can introduce disorder into [superfluid helium-3](#).
- In aircraft de-icing, a new proposal uses a [carbon nanotube](#) aerogel. A thin filament is spun on a winder to create a 10 micron-thick film, equivalent to an [A4 sheet of paper](#). The amount of material needed to cover the wings of a jumbo jet weighs 80 grams (2.8oz). Aerogel heaters could be left on continuously at low power, to prevent ice from forming.

- Thermal insulation transmission tunnel of the [Chevrolet Corvette \(C7\)](#).
- [CamelBak](#) uses aerogel as insulation in a thermal sport bottle.
- 45 North uses aerogel as palm insulation in its Sturmfist 5 cycling gloves.

Production]



[Peter Tsou](#) with a sample of aerogel at [Jet Propulsion Laboratory, California Institute of Technology](#)

Silica aerogels are typically synthesized by using a sol-gel process. The first step is the creation of a [colloidal suspension](#) of solid particles known as a "sol". The precursors are a liquid [alcohol](#) such as ethanol which is mixed with a silicon [alkoxide](#), such as tetramethoxysilane (TMOS), tetraethoxysilane (TEOS), and polyethoxydisiloxane (PEDS) (earlier work used sodium silicates). The solution of silica is mixed with a catalyst and allowed to gel during a [hydrolysis](#) reaction which forms particles of silicon dioxide. The oxide suspension begins to undergo [condensation reactions](#) which result in the creation of metal oxide bridges (either [M–O–M](#), "[oxo](#)" [bridges](#) or [M–OH–M](#), "[ol](#)" [bridges](#)) linking the dispersed colloidal particles. These reactions generally have moderately slow reaction rates, and as a result either acidic or basic [catalysts](#) are used to improve the processing speed. Basic catalysts tend to produce more transparent aerogels and minimize the shrinkage during the drying process and also strengthen it to prevent pore collapse during drying.

Finally, during the drying process of the aerogel, the liquid surrounding the silica network is carefully removed and replaced with air, while keeping the aerogel intact. Gels where the liquid is allowed to evaporate at a natural rate are known as [xerogels](#). As the liquid evaporates, forces caused by [surface tensions](#) of the liquid-solid [interfaces](#) are enough to destroy the fragile gel network. As a result, xerogels cannot achieve the high porosities and instead peak at lower porosities and exhibit large amounts of shrinkage after drying.

In 1931, to develop the first aerogels, Kistler used a process known as [supercritical drying](#) which avoids a direct phase change. By increasing the temperature and pressure he forced the liquid into a [supercritical fluid](#) state where by dropping the pressure he could instantly gasify and remove the liquid inside the aerogel, avoiding damage to the delicate three-dimensional network. While this can be done with [ethanol](#), the high temperatures and pressures lead to dangerous processing conditions. A safer, lower temperature and pressure method involves a solvent exchange. This is typically done by exchanging the initial aqueous pore liquid for a [CO₂](#)-miscible liquid such as ethanol or [acetone](#), then onto liquid carbon dioxide and then bringing the carbon dioxide above its [critical point](#). A variant on this process involves the direct injection of supercritical carbon dioxide into the pressure vessel containing the aerogel. The end result of either process exchanges the initial liquid from the gel with carbon dioxide, without allowing the gel structure to collapse or lose volume.

[Resorcinol–formaldehyde](#) aerogel (RF aerogel) is made in a way similar to production of silica aerogel. A carbon aerogel can then be made from this resorcinol–formaldehyde aerogel by [pyrolysis](#) in an [inert gas](#) atmosphere, leaving a matrix of [carbon](#). It is commercially available as solid shapes, powders, or composite paper. Additives have been successful in enhancing certain properties of the aerogel for the use of specific applications. Aerogel [composites](#) have been made using a variety of continuous and discontinuous

[reinforcements](#). The high aspect ratio of fibers such as [fiberglass](#) have been used to reinforce aerogel composites with significantly improved mechanical properties.

Safety

Silica-based aerogels are not known to be [carcinogenic](#) or toxic. However, they are a mechanical [irritant](#) to the eyes, skin, respiratory tract, and digestive system. Small silica particles can potentially cause [silicosis](#) when inhaled. They can also induce dryness of the skin, eyes, and mucous membranes. Therefore, it is recommended that protective gear including respiratory protection, gloves and eye goggles be worn whenever handling aerogels.