Aerogel

The Lightest Solid Known

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Aerogel, a material not much denser than air on a foggy morning, may provide a good number of applications to the scientific community.

It certainly looks like a whiff of smoke frozen into immobility. If you happen to hold a tile of silica aerogel, commonly called silica air-glass, you would feel practically no weight in your hands. But your mind may well be loaded with a number of questions about its origin, its structure and its properties.

Aerogel is a highly porous solid composed of 0.2% microscopic strands of silicon dioxide as a tenuous web and 99.8% air. This next to nothing solid is due to a gel from which all the liquid has been removed, leaving only a porous framework of silica with air-filled interstices. This has a density as low as 5 milligrams per cubic centimeter; that is only 4–5 times greater than the density of air at sea level. Despite its seeming lack of substance, it is strong enough to support a weight 1600 times its own weight!

Flash Back

As early as in 1864, T Graham had shown that the water in silica gel could readily be replaced by organic liquids. Biologists have taken advantage of this discovery and have successfully replaced the water from gelatinous tissues by alcohol, xylene and paraffin. The final product is a gel in which the organic material is the disperse phase instead of water (see *Box 1* for some definitions).

These facts had led S S Kistler in 1932 to the conviction that a gel, once formed, is independent of the fluid filling its meshes and that fluid might as well be a gas instead of a liquid.

Box 1

A *colloid* is a suspension in which the dispersed phase is so small (1–1000 nm) that gravitational forces are negligible and interactions are dominated by short-range forces, such as van der Waals' attraction and surface charge interactions.

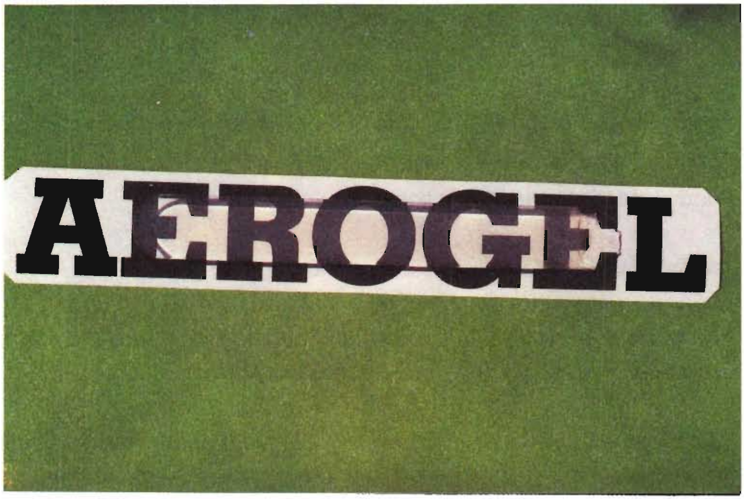
A *sol* is a colloidal suspension of solid particles in a liquid.

An *aerosol* is a colloidal suspension of particles in a gas (the suspension may be called a fog if the particles are liquid and a smoke if they are solid).

A *gel* is difficult to define precisely, although even children intuitively recognise gels. A possible description of a gel is that it is a substance that contains a continuous solid skeleton enclosing a continuous liquid phase. Typically, a polymer molecule which has reached macroscopic dimensions so that it extends throughout the solution is a gel. However, covalent linking to form a giant molecule is not a pre-requisite. Particulate gels held together by van der Waals' forces and gels formed by entangled chains are possible.

This was an important insight. But then came the tricky part; the liquid had to be removed and substituted by a gas without modifying the gel structure. Normally as liquid leaves a gel, surface tension at the liquid-vapour interface causes considerable shrinkage upon drying, making the network collapse on itself. The solution to this problem is to dry the gel at a fairly high temperature and pressure so that the liquid is in a supercritical state. In such a state there is little difference between a liquid and a gas, leading to minimum effect on surface tension. Hence, the molecules of the liquid can be slowly removed from the gel without disturbing the porous network.

Kistler's method of producing aerogels was very tedious and took several weeks to finish. A significant improvement was achieved in 1962 by Teichner and coworkers. Teichner had been approached by the French Government to design a method to store rocket propellants in porous materials. He succeeded in designing a new method to speed up the process of making the gel.



A 10 mm diameter sample of silica aerogel prepared in the author's laboratory. Note the transparency and monolithicity of the gel.

Preparation and Properties

There are several ways in which gels can be prepared. Here we shall focus on a process based on alkoxide synthesis. An alkoxide precursor such as $Si(OR)_4$ where R can be an organic group like methyl, ethyl, propyl, etc., is hydrolysed by mixing with water in the presence of the corresponding alcohol (equation 1).

$$(OR)_3Si\text{–}OR + H_2O \longrightarrow (OR)_3Si\text{–}OH + ROH \qquad (1)$$

$$(OR)_3Si\text{–}OR + HO\text{–}Si(OR)_3 \longrightarrow (OR)_3Si\text{–}O\text{–}Si(OR)_3 + ROH \qquad (2)$$

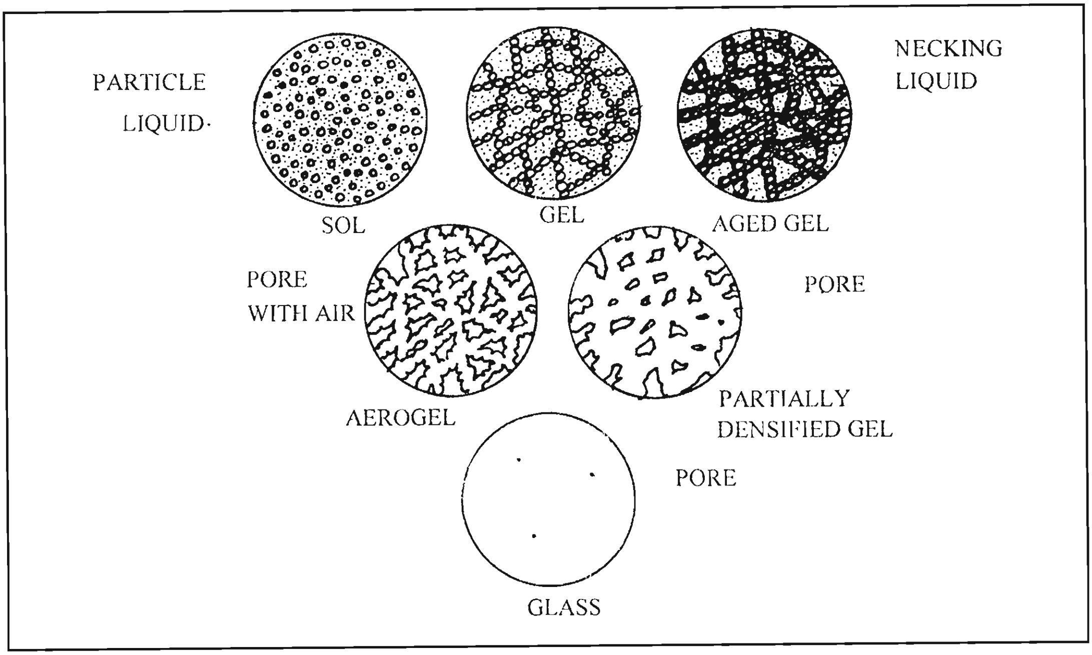
$$(OR)_3Si\text{–}OH + HO\text{–}Si(OR)_3 \longrightarrow (OR)_3Si\text{–}O\text{–}Si(OR)_3 + H_2O \qquad (3)$$

The hydrated silicate tetrahedra interact in polycondensation reactions (equations 2 and 3) forming $\equiv$Si–O–Si$\equiv$ bonds and eventually resulting in a rigid SiO_2 network. This state is called a *gel* (the state that most interests children!). This gel is then dried in an autoclave at supercritical conditions of the respective alcohol. As a result, a highly porous, low density, large surface area *silica aerogel* is produced.

- Aerogel can be used as effective and selective catalysts.
- Aerogel dust in grain and seed stocks was found to kill insects by mere water extraction from the organic tissues.
- For the detection of fast pions, kaons or protons, a medium with a refractive index close to that of air is required. Aerogel exactly fits within this range.
- Aerogel used as core material for windows would make them sound proof and also impermeable to heat.

What is so special about the aerogel? The microstructure of the aerogel resembles a bunch of pearl necklaces heaped on a table.

Figure 1 SOL-GEL processing and resulting structures.



The particle size and pore size are a few nanometers (billionths of a meter). *Figure 1* provides a comparison of the internal structures of a typical sol, different types of gels and glass.

The irregular chain-like structures in aerogel lead to some unusual properties. Aerogels are poor conductors of both heat and sound. The thermal conductivity of a good quality aerogel is nearly 9 mW/mK and the velocity of sound is as low as 100 m/s. It mostly reflects sound. When a piece of aerogel is dropped from a height, it produces a metallic ringing noise. Aerogel is transparent because the size of the structural entities are smaller than the wavelength of visible light. But due to Rayleigh scattering, the substance has a bluish tint. Aerogel has a very low refractive index ranging from 1.01 to 1.08 and a large surface area per unit volume varying from 600 m^2/g to 1000 m^2/g. These are two unusual combinations of properties of a gas and a solid.

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Applications of Aerogels

Aerogels are being developed as catalysts to promote chemical reactions, as sound insulators, as elements in sonic range- finding devices used by automatic focus cameras, and as Cherenkov radiation detectors in nuclear reactors. Another potentially valuable application of aerogel would be insulation in refrigerators, replacing foam plastic.

Aerogels are being used by NASA for collecting micrometeoroids in space. Because of their low density, aerogels should be able to capture the tiny, fast-moving particles without damaging them. As aerogels are highly transparent, the captured micrometeoroids and their paths through the material can be studied easily.

Aerogels can be densified to ultra high pure glass at relatively low temperatures (1200°C) when compared to commercial glass manufacture (which is done at 2000°C). Partially densified porous glass provides a host matrix for the incorporation of organic or inorganic species, for a variety of applications.

The future potential of this novel aerogel material is endless. Its fascinating features make possible applications, either directly or as a host material, in a wide range of optical products, lenses, wave guides, optical fibers, filters, dye lasers and nonlinear optical devices. One can expect many more new hybrid optical components with multiple functions in the next few years.

A particularly nice feature about silica aerogel is that it is environment-friendly. The substance consists of the same structural entities that make up common beach sand. When exposed to water the material simply disintegrates into fine sand. What better hi-tech material could one ask for?

Suggested Reading

- R K Iler. *The Chemistry of Silica.* Wiley. New York, 1979.
- D W Schaefer and K D Keefer. *Better Ceramics Through Chemistry.* Elsevier-North Holland/ N. Y., 1984.
- J Fricke. Ed. *Aerogels.* Springer Verlag. Heidelberg, 1986.
- C J Brinker and G W Scherer. *Sol-Gel Science: The Physics and Chemistry of Sol-Gel Processing.* Academic Press. Boston, 1990.

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