

**ENGINEERING MATERIALS**

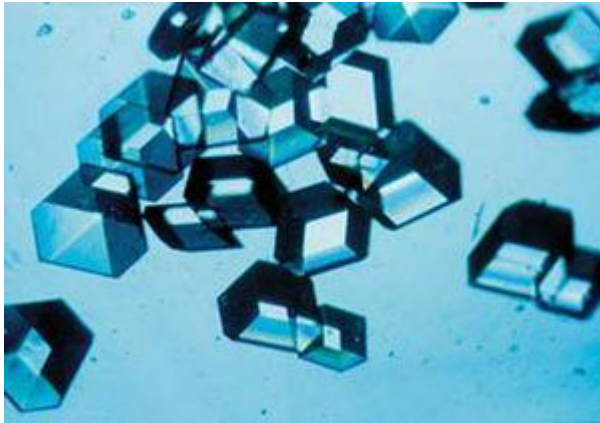
**ELECTRICAL DIPLOMA COURSE**


# Solid

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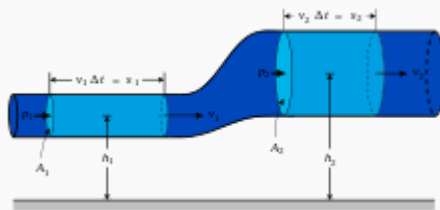
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For other uses, see [Solid \(disambiguation\)](#).



 Single crystalline form of solid [Insulin](#).

## Continuum mechanics



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**Solid** is one of [the four fundamental states of matter](#) (the others being [liquid](#), [gas](#), and [plasma](#)). It is characterized by structural rigidity and resistance to changes of shape or volume. Unlike a [liquid](#), a solid object does not flow to take on the shape of its container, nor does it expand to fill the entire volume available to it like a [gas](#) does. The atoms in a solid are tightly bound to each other, either in a regular geometric lattice ([crystalline solids](#), which include [metals](#) and ordinary [water ice](#)) or irregularly (an [amorphous solid](#) such as common window [glass](#)).

The branch of [physics](#) that deals with solids is called [solid-state physics](#), and is the main branch of [condensed matter physics](#) (which also includes liquids). [Materials science](#) is primarily concerned with the physical and [chemical](#) properties of solids. [Solid-state chemistry](#) is especially concerned with the [synthesis](#) of novel materials, as well as the science of identification and [chemical composition](#).

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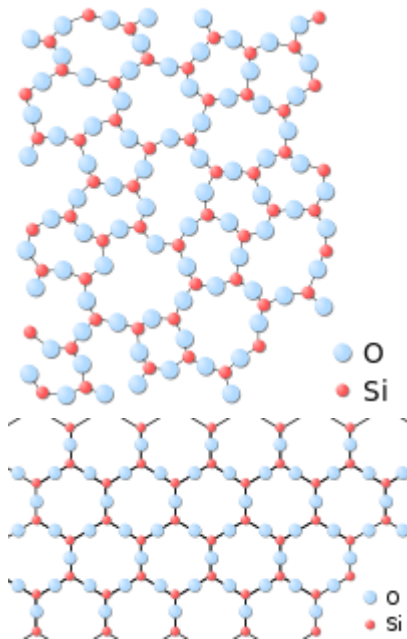
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Model of closely packed atoms within a crystalline solid.

The atoms, molecules or ions which make up a solid may be arranged in an orderly repeating pattern, or irregularly. Materials whose constituents are arranged in a regular pattern are known as [crystals](#). In some cases, the regular ordering can continue unbroken over a large scale, for example [diamonds](#), where each diamond is a [single crystal](#). Solid objects that are large enough to see and handle are rarely composed of a single crystal, but instead are made of a large number of single crystals, known as [crystallites](#), whose size can vary from a few nanometers to several meters. Such materials are called [polycrystalline](#). Almost all common metals, and many [ceramics](#), are polycrystalline.



Schematic representation of a random-network glassy form (left) and ordered crystalline lattice (right) of identical chemical composition.

In other materials, there is no long-range order in the position of the atoms. These solids are known as [amorphous solids](#); examples include [polystyrene](#) and [glass](#).

Whether a solid is crystalline or amorphous depends on the material involved, and the conditions in which it was formed. Solids which are formed by slow cooling will tend to be crystalline, while solids which are frozen rapidly are more likely to be amorphous. Likewise, the specific [crystal structure](#) adopted by a crystalline solid depends on the material involved and on how it was formed.

While many common objects, such as an ice cube or a coin, are chemically identical throughout, many other common materials comprise a number of different substances packed together. For example, a typical [rock](#) is an aggregate of several different [minerals](#) and [mineraloids](#), with no specific chemical composition. [Wood](#) is a natural organic material consisting primarily of [cellulose](#) fibers embedded in a matrix of organic [lignin](#). In materials science, [composites](#) of more than one constituent material can be designed to have desired properties.

## [\[edit\]](#) **Classes of solids**

*Further information:* [Bonding in solids](#)

The forces between the atoms in a solid can take a variety of forms. For example, a crystal of [sodium chloride](#) (common salt) is made up of [ionic sodium](#) and [chlorine](#), which are held together by [ionic bonds](#). In diamond or silicon, the atoms share [electrons](#) and form [covalent bonds](#). In metals, electrons are shared in [metallic bonding](#). Some solids, particularly most organic compounds, are held together with [van der Waals forces](#) resulting from the polarization of the electronic charge cloud on each molecule. The dissimilarities between the types of solid result from the differences between their bonding.

## [\[edit\]](#) **Metals**

*Main article:* [Metal](#)



The pinnacle of New York's [Chrysler Building](#), the world's tallest steel-supported brick building, is clad with stainless steel.

Metals typically are strong, dense, and good conductors of both [electricity](#) and [heat](#). The bulk of the elements in the [periodic table](#), those to the left of a diagonal line drawn from [boron](#) to [polonium](#), are metals. Mixtures of two or more elements in which the major component is a metal are known as [alloys](#).

People have been using metals for a variety of purposes since prehistoric times. The [strength](#) and [reliability](#) of metals has led to their widespread use in [construction](#) of buildings and other structures, as well as in most vehicles, many appliances and tools, pipes, road signs and railroad tracks. [Iron](#) and [aluminium](#) are the two most commonly used structural metals, and they are also the most abundant metals in the [Earth's crust](#). Iron is most commonly used in the form of an alloy, [steel](#), which contains up to 2.1% [carbon](#), making it much harder than pure iron.

Because metals are good conductors of electricity, they are valuable in [electrical](#) appliances and for carrying an [electric current](#) over long distances with little energy loss or dissipation. Thus, electrical power grids rely on metal cables to distribute electricity. Home electrical systems, for example, are wired with copper for its good conducting properties and easy machinability. The high [thermal conductivity](#) of most metals also makes them useful for stovetop cooking utensils.

The study of [metallic](#) elements and their [alloys](#) makes up a significant portion of the fields of solid-state chemistry, physics, materials science and engineering.

Metallic solids are held together by a high density of shared, delocalized electrons, known as "[metallic bonding](#)". In a metal, atoms readily lose their outermost ("valence") [electrons](#), forming positive [ions](#). The free electrons are spread over the entire solid, which is held together firmly by electrostatic interactions between the ions and the electron cloud.<sup>[1]</sup> The large number of [free electrons](#) gives metals their high values of electrical and thermal conductivity. The free electrons also prevent transmission of visible light, making metals opaque, shiny and [lustrous](#).

More advanced models of metal properties consider the effect of the positive ions cores on the delocalised electrons. As most metals have crystalline structure, those ions are usually arranged into a periodic lattice. Mathematically, the potential of the ion cores can be treated by various models, the simplest being the [nearly free electron model](#).

## [\[edit\]](#) Minerals



A collection of various minerals.

*Main article:* [Minerals](#)

[Minerals](#) are naturally occurring solids formed through various [geological](#) processes under high pressures. To be classified as a true mineral, a substance must have a [crystal structure](#) with uniform physical properties throughout. Minerals range in composition from pure [elements](#) and simple [salts](#) to very complex [silicates](#) with thousands of known forms. In

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## [\[edit\]](#) **Ceramics**



Si<sub>3</sub>N<sub>4</sub> ceramic bearing parts

*Main article:* [Ceramic engineering](#)

Ceramic solids are composed of inorganic compounds, usually [oxides](#) of chemical elements. They are chemically inert, and often are capable of withstanding chemical erosion that occurs in an acidic or caustic environment. Ceramics generally can withstand high temperatures ranging from 1000 to 1600 °C (1800 to 3000 °F). Exceptions include non-oxide inorganic materials, such as [nitrides](#), [borides](#) and [carbides](#).

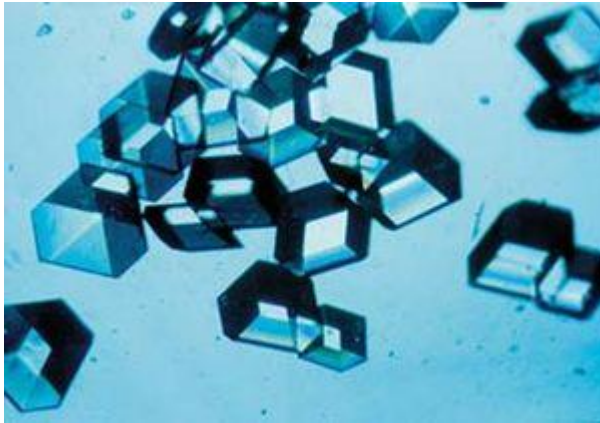
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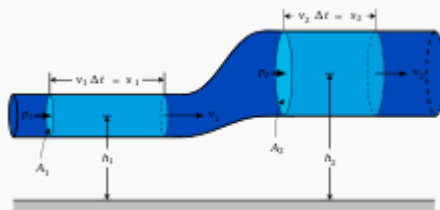
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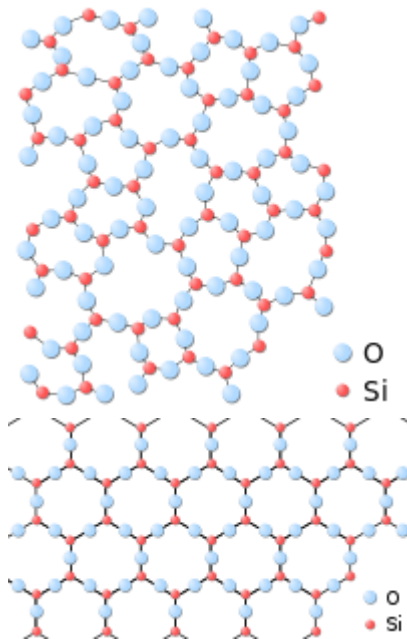
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# Liquid

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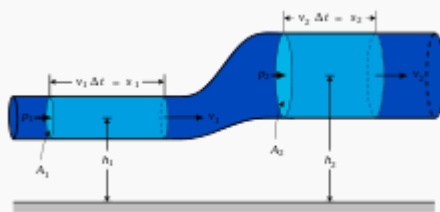
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*For other uses, see [Liquid \(disambiguation\)](#).*



The formation of a spherical [droplet](#) of liquid water minimizes the [surface area](#), which is the natural result of [surface tension](#) in liquids.

## Continuum mechanics



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**Liquid** is one of the [the four fundamental states of matter](#) (the others being [solid](#), [gas](#), and [plasma](#)), and is the only state with a definite volume but no fixed shape. A liquid is made up of tiny vibrating particles of matter, such as atoms and molecules, held together by

intramolecular bonds. Water is, by far, the most common liquid on Earth. Like a gas, a liquid is [able to flow](#) and take the shape of a container. Some liquids resist compression, while others can be compressed. Unlike a gas, a liquid does not disperse to fill every space of a container, and maintains a fairly constant density. A distinctive property of the liquid state is [surface tension](#), leading to [wetting](#) phenomena.

The density of a liquid is usually close to that of a solid, and much higher than in a gas. Therefore, liquid and solid are both termed [condensed matter](#). On the other hand, as liquids and gases share the ability to flow, they are both called [fluids](#). Although liquid water is abundant on Earth, this state of matter is actually the least common in the known universe, because liquids require a relatively narrow temperature/pressure range to exist. Most known matter in the universe is in gaseous form (with traces of detectable solid matter) as interstellar clouds or in plasma form within stars.

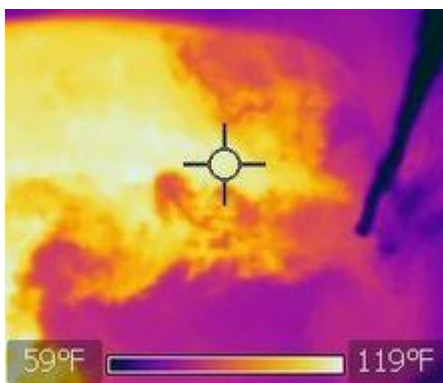
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## [\[edit\]](#) Introduction





Thermal image of a sink full of hot water with cold water being added, showing how the hot and the cold water flow into each other.

Liquid is one of the three primary [states of matter](#), with the others being [solid](#) and [gas](#). A liquid is a [fluid](#). Unlike a solid, the [molecules](#) in a liquid have a much greater freedom to move. The forces that bind the molecules together in a solid are only temporary in a liquid, allowing a liquid to flow while a solid remains rigid.

A liquid, like a gas, displays the properties of a fluid. A liquid can flow, assume the shape of a container, and, if placed in a sealed container, will distribute applied pressure evenly to every surface in the container. Unlike a gas, a liquid may not always mix readily with another liquid, will not always fill every space in the container, forming its own surface, and will not compress significantly, except under extremely high pressures. These properties make a liquid suitable for applications such as [hydraulics](#).

Liquid particles are bound firmly but not rigidly. They are able to move around one another freely, resulting in a limited degree of particle mobility. As the [temperature](#) increases, the increased vibrations of the molecules causes distances between the molecules to increase. When a liquid reaches its [boiling point](#), the cohesive forces that bind the molecules closely together break, and the liquid changes to its gaseous state (unless [superheating](#) occurs). If the temperature is decreased, the distances between the molecules become smaller. When the liquid reaches its [freezing point](#) the molecules will usually lock into a very specific order, called crystallizing, and the bonds between them become more rigid, changing the liquid into its solid state (unless [supercooling](#) occurs).

## [\[edit\]](#) Examples

Only two [elements](#) are liquid at [standard conditions for temperature and pressure](#): [mercury](#) and [bromine](#). Four more elements have melting points slightly above [room temperature](#): [francium](#), [caesium](#), [gallium](#) and [rubidium](#).<sup>[1]</sup> Metal alloys that are liquid at room temperature include [NaK](#), a sodium-potassium metal alloy, [galinstan](#), a fusible alloy liquid, and some [amalgams](#) (alloys involving mercury).

Pure substances that are liquid under normal conditions include [water](#), [ethanol](#) and many other organic solvents. Liquid water is of vital importance in chemistry and biology; it is believed to be a necessity for the existence of [life](#).



Important everyday liquids include aqueous [solutions](#) like household [bleach](#), other [mixtures](#) of different substances such as [mineral oil](#) and [gasoline](#), [emulsions](#) like [vinaigrette](#) or [mayonnaise](#), [suspensions](#) like [blood](#), and [colloids](#) like [paint](#) and [milk](#).

Many gases can be [liquefied](#) by cooling, producing liquids such as [liquid oxygen](#), [liquid nitrogen](#), [liquid hydrogen](#) and [liquid helium](#). Not all gases can be liquified at atmospheric pressure, for example [carbon dioxide](#) can only be liquified at pressures above 5.1 [atm](#).

Some materials cannot be classified within the classical three states of matter; they possess solid-like and liquid-like properties. Examples include [liquid crystals](#), used in LCD displays, and [biological membranes](#).

## **[edit]** Applications

Liquids have a variety of uses, as lubricants, solvents, and coolants. In hydraulic systems, liquid is used to transmit power.

In [tribology](#), liquids are studied for their properties as [lubricants](#). Lubricants such as [oil](#) are chosen for [viscosity](#) and flow characteristics that are suitable throughout the [operating temperature](#) range of the component. Oils are often used in [engines](#), [gear boxes](#), [metalworking](#), and hydraulic systems for their good lubrication properties.<sup>[2]</sup>

Many liquids are used as [solvents](#), to dissolve other liquids or solids. [Solutions](#) are found in a wide variety of applications, including [paints](#), [sealants](#), and [adhesives](#). [Naphtha](#) and [acetone](#) are used frequently in industry to clean oil, grease, and tar from parts and machinery. [Body fluids](#) are water based solutions.

[Surfactants](#) are commonly found in [soaps](#) and [detergents](#). Solvents like [alcohol](#) are often used as [antimicrobials](#). They are found in [cosmetics](#), [inks](#), and liquid [dye lasers](#). They are used in the food industry, in processes such as the extraction of [vegetable oil](#).<sup>[3]</sup>

Liquids tend to have better [thermal conductivity](#) than gases, and the ability to flow makes a liquid suitable for removing excess heat from mechanical components. The heat can be removed by channeling the liquid through a [heat exchanger](#), such as a [radiator](#), or the heat can be removed with the liquid during [evaporation](#).<sup>[4]</sup> Water or [glycol](#) coolants are used to keep [engines](#) from overheating.<sup>[5]</sup> The coolants used in [nuclear reactors](#) include water or liquid metals, such as [sodium](#) or [bismuth](#).<sup>[6]</sup> [Liquid propellant](#) films are used to cool the thrust chambers of [rockets](#).<sup>[7]</sup> In [machining](#), water and oils are used to remove the excess heat generated, which can quickly ruin both the work piece and the tooling. During [perspiration](#), sweat removes heat from the human body by evaporating. In the [heating, ventilation, and air-conditioning](#) industry (HVAC), liquids such as water are used to transfer heat from one area to another.<sup>[8]</sup>

Liquid is the primary component of [hydraulic](#) systems, which take advantage of [Pascal's law](#) to provide [fluid power](#). Devices such as [pumps](#) and [waterwheels](#) have been used to change liquid motion into [mechanical work](#) since ancient times. [Oils](#) are forced through [hydraulic pumps](#), which transmit this force to [hydraulic cylinders](#). Hydraulics can be found in many applications, such as [automotive brakes](#) and [transmissions](#), [heavy equipment](#), and [airplane](#)

control systems. Various [hydraulic presses](#) are used extensively in repair and manufacturing, for lifting, pressing, clamping and forming.<sup>[9]</sup>

Liquids are sometimes used in measuring devices. A [thermometer](#) often uses the [thermal expansion](#) of liquids, such as [mercury](#), combined with their ability to flow to indicate temperature. A [manometer](#) uses the weight of the liquid to indicate [air pressure](#).<sup>[10]</sup>

## **[edit]** Mechanical properties

### **[edit]** Volume

Quantities of liquids are commonly measured in units of [volume](#). These include the [SI](#) unit [cubic metre](#) (m<sup>3</sup>) and its divisions, in particular the cubic decimetre, more commonly called the [litre](#) (1 dm<sup>3</sup> = 1 L = 0.001 m<sup>3</sup>), and the cubic centimetre, also called millilitre (1 cm<sup>3</sup> = 1 mL = 0.001 L = 10<sup>−6</sup> m<sup>3</sup>).

The [volume](#) of a quantity of liquid is fixed by its [temperature](#) and [pressure](#). Liquids generally expand when heated, and contract when cooled. [Water](#) between 0 °C and 4 °C is a notable exception. Liquids have little [compressibility](#): water, for example, requires a pressure of the order of 200 bar to increase its [density](#) by 1/1000. In the study of [fluid dynamics](#), liquids are often treated as [incompressible](#), especially when studying [incompressible flow](#).

### **[edit]** Pressure and buoyancy

*Main article: [fluid statics](#)*

In a [gravitational field](#), liquids exert [pressure](#) on the sides of a container as well as on anything within the liquid itself. This pressure is transmitted in all directions and increases with depth. If a liquid is at rest in a uniform gravitational field, the pressure, *p*, at any depth, *z*, is given by

$$p = \rho g z$$

where:

*ρ* is the [density](#) of the liquid (assumed constant)

*g* is the [gravitational acceleration](#).

Note that this formula assumes that the pressure *at* the free surface is zero, and that [surface tension](#) effects may be neglected.

Objects immersed in liquids are subject to the phenomenon of [buoyancy](#). (Buoyancy is also observed in other fluids, but is especially strong in liquids due to their high density.)

### **[edit]** Surfaces

*Main article: [surface science](#)*



[Surface waves](#) in [water](#)

Unless the volume of a liquid exactly matches the volume of its container, one or more surfaces are observed. The surface of a liquid behaves like an elastic membrane in which [surface tension](#) appears, allowing the formation of [drops](#) and [bubbles](#). [Surface waves](#), [capillary action](#), [wetting](#), and [ripples](#) are other consequences of [surface tension](#).

### [\[edit\]](#) **Flow**

*Main article:* [fluid mechanics](#)

*Main article:* [fluid dynamics](#)

[Viscosity](#) measures the resistance of a liquid which is being deformed by either shear stress or extensional stress.

When a liquid is [supercooled](#) towards the [glass transition](#), the viscosity increases dramatically! The liquid then becomes a [viscoelastic](#) medium that shows both the [elasticity](#) of a solid and the fluidity of a liquid, depending on the time scale of observation or on the frequency of perturbation.

### [\[edit\]](#) **Sound propagation**

*Main article:* [speed of sound#Speed of sound in liquids](#)

In a fluid the only non-zero [stiffness](#) is to volumetric deformation (a fluid does not sustain shear forces). Hence the speed of sound in a fluid is given by  $c = \sqrt{K/\rho}$  where  $K$  is the [bulk modulus](#) of the fluid, and  $\rho$  the density. To give a typical value, in fresh water  $c=1497$  m/s at 25 °C.

## [\[edit\]](#) **Thermodynamics**

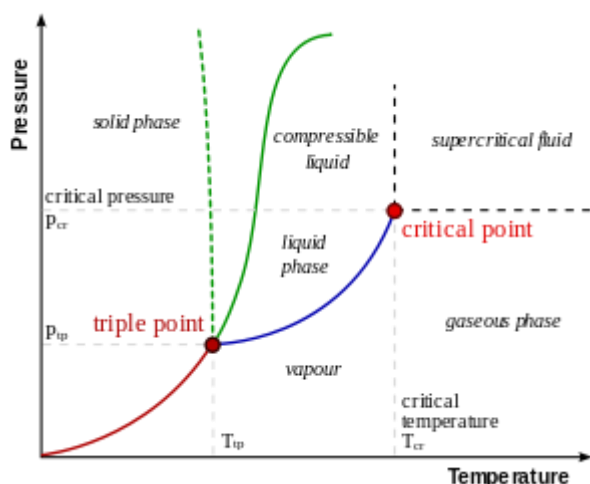
### [\[edit\]](#) **Phase transitions**

*Main article:* [boiling](#)

*Main article:* [boiling point](#)

*Main article:* [melting](#)

Main article: [melting point](#)



A typical [phase diagram](#). The dotted line gives the anomalous behaviour of [water](#). The green lines show how the [freezing point](#) can vary with pressure, and the blue line shows how the [boiling point](#) can vary with pressure. The red line shows the boundary where [sublimation](#) or [deposition](#) can occur.

At a temperature below the [boiling point](#), any matter in liquid form will evaporate until the condensation of gas above reach an equilibrium. At this point the gas will condense at the same rate as the liquid evaporates. Thus, a liquid cannot exist permanently if the evaporated liquid is continually removed. A liquid at its [boiling point](#) will evaporate more quickly than the gas can condense at the current pressure. A liquid at or above its boiling point will normally boil, though [superheating](#) can prevent this in certain circumstances.

At a temperature below the freezing point, a liquid will tend to [crystallize](#), changing to its solid form. Unlike the transition to gas, there is no equilibrium at this transition under constant pressure, so unless [supercooling](#) occurs, the liquid will eventually completely crystallize. Note that this is only true under constant pressure, so e.g. water and ice in a closed, strong container might reach an equilibrium where both phases coexist. For the opposite transition from solid to liquid, see [melting](#).

## [\[edit\]](#) Solutions

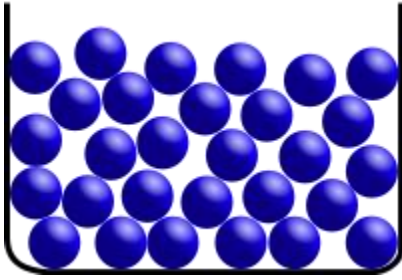
Main article: [solution](#)

Liquids can display [immiscibility](#). The most familiar mixture of two immiscible liquids in everyday life is the [vegetable oil](#) and [water](#) in [Italian salad dressing](#). A familiar set of miscible liquids is water and alcohol. Liquid components in a mixture can often be separated from one another via [fractional distillation](#).

## [\[edit\]](#) Microscopic properties

### [\[edit\]](#) Static structure factor

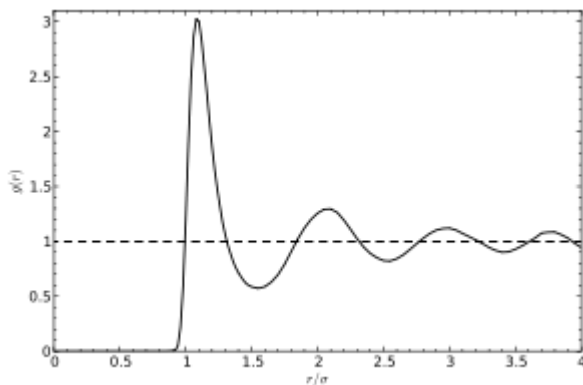
Main article: [structure of liquids and glasses](#)



Structure of a classical monatomic liquid. Atoms have many nearest neighbors in contact, yet no long-range order is present.

In a liquid, atoms do not form a crystalline lattice, nor do they show any other form of [long-range order](#). This is evidenced by the absence of [Bragg peaks](#) in [X-ray](#) and [neutron diffraction](#). Under normal conditions, the diffraction pattern has circular symmetry, expressing the [isotropy](#) of the liquid. In radial direction, the diffraction intensity smoothly oscillates. This is usually described by the [static structure factor](#)  $S(q)$ , with wavenumber  $q=(4\pi/\lambda)\sin\theta$  given by the wavelength  $\lambda$  of the probe (photon or neutron) and the [Bragg angle](#)  $\theta$ . The oscillations of  $S(q)$  express the *near order* of the liquid, i.e. the correlations between an atom and a few shells of nearest, second nearest, ... neighbors.

A more intuitive description of these correlations is given by the [radial distribution function](#)  $g(r)$ , which is basically the [Fourier transform](#) of  $S(q)$ . It represents a spatial average of a temporal snapshot of [pair correlations](#) in the liquid.



Radial distribution function of the [Lennard-Jones model fluid](#).

### [\[edit\]](#) Sound dispersion and structural relaxation

The above expression for the sound velocity  $c = \sqrt{K/\rho}$  contains the [bulk modulus](#)  $K$ . If  $K$  is frequency independent then the liquid behaves as a [linear medium](#), so that sound propagates without [dissipation](#) and without [mode coupling](#). In reality, any liquid shows some [dispersion](#): with increasing frequency,  $K$  crosses over from the low-frequency, liquid-like limit  $K_0$  to the high-frequency, solid-like limit  $K_\infty$ . In normal liquids, most of this cross over takes place at frequencies between GHz and THz, sometimes called [hypersound](#).

At sub-GHz frequencies, a normal liquid cannot sustain [shear waves](#): the zero-frequency limit of the [shear modulus](#) is  $G_0 = 0$ . This is sometimes seen as the defining property of a liquid.<sup>[11]</sup> However, just as the bulk modulus  $K$ , the shear modulus  $G$  is frequency dependent, and at hypersound frequencies it shows a similar cross over from the liquid-like limit  $G_0$  to a solid-like, non-zero limit  $G_\infty$ .

According to the [Kramers-Kronig relation](#), the dispersion in the sound velocity (given by the real part of  $K$  or  $G$ ) goes along with a maximum in the sound attenuation (dissipation, given by the imaginary part of  $K$  or  $G$ ). According to [linear response theory](#), the Fourier transform of  $K$  or  $G$  describes how the system returns to equilibrium after an external perturbation; for this reason, the dispersion step in the GHz..THz region is also called [structural relaxation](#). According the [fluctuation-dissipation theorem](#), relaxation *towards* equilibrium is intimately connected to fluctuations *in* equilibrium. The density fluctuations associated with sound waves can be experimentally observed by [Brillouin scattering](#).

On supercooling a liquid towards the glass transition, the crossover from liquid-like to solid-like response moves from GHz to MHz, kHz, Hz, ...; equivalently, the characteristic time of structural relaxation increases from ns to  $\mu$ s, ms, s, ... This is the microscopic explanation for the above mentioned viscoelastic behaviour of glass-forming liquids.

## [\[edit\]](#) Effects of association

The mechanisms of atomic/molecular [diffusion](#) (or [particle displacement](#)) in solids are closely related to the mechanisms of viscous flow and solidification in liquid materials. Descriptions of [viscosity](#) in terms of molecular "free space" within the liquid<sup>[12]</sup> were modified as needed in order to account for liquids whose molecules are known to be "associated" in the liquid state at ordinary temperatures. When various molecules combine together to form an associated molecule, they enclose within a semi-rigid system a certain amount of space which before was available as free space for mobile molecules. Thus, increase in viscosity upon cooling due to the tendency of most substances to become *associated* on cooling.<sup>[13]</sup>

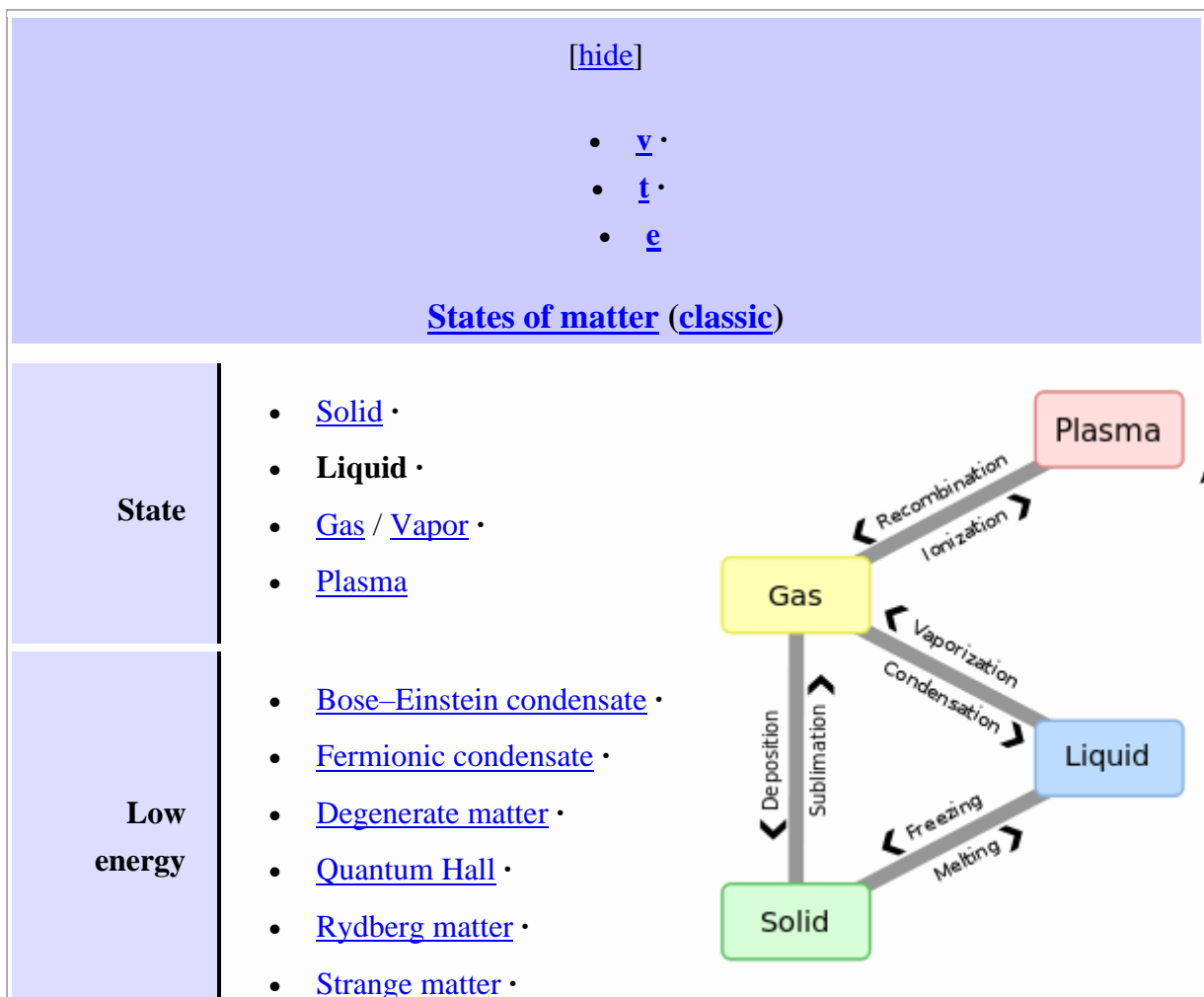
Similar arguments could be used to describe the effects of [pressure](#) on viscosity, where it may be assumed that the viscosity is chiefly a function of the volume for liquids with a finite [compressibility](#). An increasing viscosity with rise of pressure is therefore expected. In addition, if the volume is expanded by heat but reduced again by pressure, the viscosity remains the same.

The local tendency to orientation of molecules in small groups lends the liquid (as referred to previously) a certain degree of association. This association results in a considerable "internal pressure" within a liquid, which is due almost entirely to those molecules which, on account of their temporary low velocities (following the Maxwell distribution) have coalesced with other molecules. The internal pressure between several such molecules might correspond to that between a group of molecules in the solid form.

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	<ul style="list-style-type: none"> <li>• <a href="#">Superfluid</a> ·</li> <li>• <a href="#">Supersolid</a></li> </ul>
<p><b>High energy</b></p>	<ul style="list-style-type: none"> <li>• <a href="#">QCD matter</a> ·</li> <li>• <a href="#">Quark–gluon plasma</a> ·</li> <li>• <a href="#">Supercritical fluid</a></li> </ul>
<p><b>Other states</b></p>	<ul style="list-style-type: none"> <li>• <a href="#">Colloid</a> ·</li> <li>• <a href="#">Glass</a> ·</li> <li>• <a href="#">Liquid crystal</a> ·</li> <li>• Magnetically ordered</li> </ul> <p>(</p> <ul style="list-style-type: none"> <li>○ <a href="#">Antiferromagnet</a> ·</li> <li>○ <a href="#">Ferrimagnet</a> ·</li> <li>○ <a href="#">Ferromagnet</a></li> </ul> <p>)</p> <p>·</p> <ul style="list-style-type: none"> <li>• <a href="#">String-net liquid</a> ·</li> <li>• <a href="#">Superglass</a></li> </ul>
<p><b><u>Transition</u></b> <b>s</b></p>	<ul style="list-style-type: none"> <li>• <a href="#">Boiling</a> ·</li> <li>• <a href="#">Boiling point</a> ·</li> <li>• <a href="#">Condensation</a> ·</li> <li>• <a href="#">Critical line</a> ·</li> <li>• <a href="#">Critical point</a> ·</li> <li>• <a href="#">Crystallization</a> ·</li> <li>• <a href="#">Deposition</a> ·</li> <li>• <a href="#">Evaporation</a> ·</li> </ul>



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<b>Quantities</b>	<ul style="list-style-type: none"> <li>• <a href="#">Enthalpy of fusion</a> ·</li> <li>• <a href="#">Enthalpy of sublimation</a> ·</li> <li>• <a href="#">Enthalpy of vaporization</a> ·</li> <li>• <a href="#">Latent heat</a> ·</li> <li>• <a href="#">Latent internal energy</a> ·</li> <li>• <a href="#">Trouton's ratio</a> ·</li> <li>• <a href="#">Volatility</a></li> </ul>

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## Gas

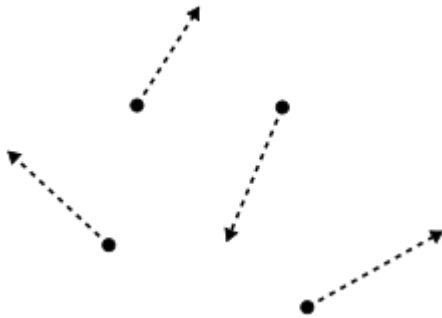
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*This article is about the physical properties of gas as a state of matter. For the uses of gases, and other meanings, see [Gas \(disambiguation\)](#).*

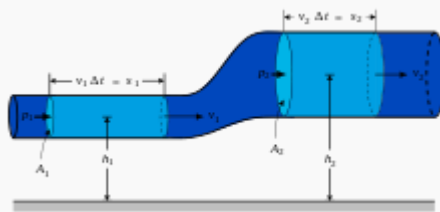


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Gas phase particles ([atoms](#), [molecules](#), or [ions](#)) move around freely in the absence of an applied [electric field](#).

## Continuum mechanics



Laws[\[show\]](#)

•

[Solid mechanics](#)[\[show\]](#)

[Fluid mechanics](#)[\[show\]](#)

[Rheology](#)[\[show\]](#)

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Scientists[\[show\]](#)

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**Gas** is one of [the four fundamental states of matter](#) (the others being [solid](#), [liquid](#), and [plasma](#)). A pure gas may be made up of individual atoms (e.g. a [noble gas](#) or atomic gas like [neon](#)), [elemental](#) molecules made from one type of atom (e.g. [oxygen](#)), or [compound](#) molecules made from a variety of atoms (e.g. [carbon dioxide](#)). A gas [mixture](#) would contain a variety of pure gases much like the [air](#). What distinguishes a gas from liquids and solids is the vast separation of the individual gas particles. This separation usually makes a colorless gas invisible to the human observer. The interaction of gas particles in the presence of electric and [gravitational fields](#) are considered negligible as indicated by the constant velocity vectors in the image.

The gaseous state of matter is found between the liquid and plasma states,<sup>[1]</sup> the latter of which provides the upper temperature boundary for gases. Bounding the lower end of the [temperature](#) scale lie degenerative quantum gases<sup>[2]</sup> which are gaining increased attention these days.<sup>[3]</sup> High-density atomic gases super cooled to incredibly low temperatures are classified by their statistical behavior as either a [Bose gas](#) or a [Fermi gas](#). For a comprehensive listing of these exotic states of matter see [list of states of matter](#).

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## Etymology

The word *gas* is a [neologism](#) first used by the early 17th century [Flemish chemist J.B. Van Helmont](#).<sup>[4]</sup> Van Helmont's word appears to have been simply a phonetic transcription of the [Greek](#) word χάος [Chaos](#) – the *g* in Dutch being pronounced like the English *ch* – in which case Van Helmont was simply following the established [alchemical](#) usage first attested in the works of [Paracelsus](#). According to Paracelsus's terminology, *chaos* meant something like "ultra-rarefied water".<sup>[5]</sup>

## Physical characteristics



Drifting [smoke](#) particles provide clues to the movement of the surrounding gas.

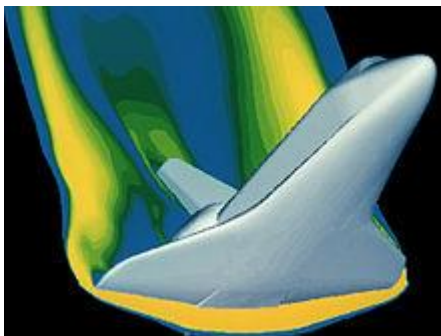
As most gases are difficult to observe directly, they are described through the use of four [physical properties](#) or [macroscopic](#) characteristics: [pressure](#), [volume](#), [number of particles](#) (chemists group them by [moles](#)) and [temperature](#). These four characteristics were repeatedly observed by scientists such as [Robert Boyle](#), [Jacques Charles](#), [John Dalton](#), [Joseph Gay-Lussac](#) and [Amedeo Avogadro](#) for a variety of gases in various settings. Their detailed studies ultimately led to a mathematical relationship among these properties expressed by the [ideal gas law](#) (see simplified models section below).

Gas particles are widely separated from one another, and consequently have weaker intermolecular bonds than liquids or solids. These [intermolecular forces](#) result from electrostatic interactions between gas particles. Like-charged areas of different gas particles repel, while oppositely charged regions of different gas particles attract one another; gases that contain permanently charged [ions](#) are known as [plasmas](#). Gaseous compounds with [polar covalent](#) bonds contain permanent charge imbalances and so experience relatively strong intermolecular forces, although the molecule while the compound's net charge remains

neutral. Transient, randomly-induced charges exist across non-polar [covalent bonds](#) of molecules and electrostatic interactions caused by them are referred to as [Van der Waals forces](#). The interaction of these intermolecular forces varies within a substance which determines many of the physical properties unique to each gas.<sup>[6][7]</sup> A comparison of *boiling points* for compounds formed by ionic and covalent bonds leads us to this conclusion.<sup>[8]</sup> The drifting smoke particles in the image provides some insight into low pressure gas behavior.

Compared to the other states of matter, gases have low [density](#) and [viscosity](#). [Pressure](#) and [temperature](#) influence the particles within a certain volume. This variation in particle separation and speed is referred to as *compressibility*. This particle separation and size influences optical properties of gases as can be found in the following [list of refractive indices](#). Finally, gas particles spread apart or [diffuse](#) in order to homogeneously distribute themselves throughout any container.

## Macroscopic



Shuttle imagery of re-entry phase.

When observing a gas, it is typical to specify a frame of reference or [length scale](#). A *larger* length scale corresponds to a [macroscopic](#) or global point of view of the gas. This region (referred to as a volume) must be sufficient in size to contain a large sampling of gas particles. The resulting statistical analysis of this sample size produces the "**average**" behavior (i.e. velocity, temperature or pressure) of all the gas particles within the region. In contrast, a *smaller* length scale corresponds to a [microscopic](#) or particle point of view.

Macroscopically, the gas characteristics measured are either in terms of the gas particles themselves (velocity, pressure, or temperature) or their surroundings (volume). For example, Robert Boyle studied [pneumatic chemistry](#) for a small portion of his career. One of his experiments related the [macroscopic](#) properties of pressure and volume of a gas. His experiment used a J-tube [manometer](#) which looks like a [test tube](#) in the shape of the letter J. Boyle trapped an [inert](#) gas in the closed end of the test tube with a column of [mercury](#), thereby making the number of particles and the temperature constant. He observed that when the pressure was increased in the gas, by adding more mercury to the column, the trapped gas' volume decreased (this is known as an [inverse](#) relationship). Furthermore, when Boyle multiplied the pressure and volume of each observation, the [product](#) was constant. This relationship held for every gas that Boyle observed leading to the law, ( $PV=k$ ), named to honor his work in this field.

There are many mathematical tools available for analyzing gas properties. As gases are subjected to extreme conditions, these tools become a bit more complex, from the [Euler](#)

[equations](#) for inviscid flow to the [Navier-Stokes equations](#)<sup>[9]</sup> that fully account for viscous effects. These equations are adapted to the conditions of the gas system in question. Boyle's lab equipment allowed the use of [algebra](#) to obtain his analytical results. His results were possible because he was studying gases in relatively low pressure situations where they behaved in an "ideal" manner. These ideal relationships apply to safety calculations for a variety of flight conditions on the materials in use. The high technology equipment in use today was designed to help us safely explore the more exotic operating environments where the gases no longer behave in an "ideal" manner. This advanced math, including [statistics](#) and [multivariable calculus](#), makes possible the solution to such complex dynamic situations as space vehicle reentry. An example is the analysis of the space shuttle reentry pictured to ensure the material properties under this loading condition are appropriate. In this flight regime, the gas is no longer behaving ideally.

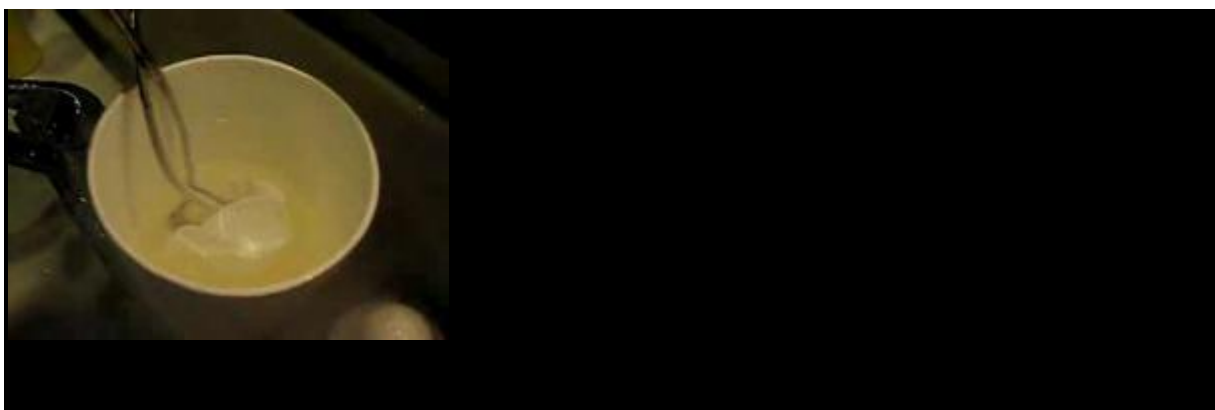
## Pressure

*Main article:* [Pressure](#)

The symbol used to represent *pressure* in equations is "**p**" or "**P**" with SI units of [pascals](#).

When describing a container of gas, the term [pressure](#) (or absolute pressure) refers to the average force per unit area that the gas exerts on the surface of the container. Within this volume, it is sometimes easier to visualize the gas particles moving in straight lines until they collide with the container (see diagram at top of the article). The force imparted by a gas particle into the container during this collision is the change in [momentum](#) of the particle.<sup>[10]</sup> During a collision only the [normal \(geometry\)](#) component of velocity changes. A particle traveling parallel to the wall does not change its momentum. Therefore the average force on a surface must be the average change in [linear momentum](#) from all of these gas particle collisions. Pressure is the sum of all the [normal components](#) of force exerted by the particles impacting the walls of the container divided by the surface area of the wall.

## Temperature



Air balloon shrinks after submersion in liquid nitrogen

*Main article:* [Thermodynamic temperature](#)

The symbol used to represent *temperature* in equations is *T* with SI units of [kelvins](#).

The speed of a gas particle is proportional to its [absolute temperature](#). The volume of the balloon in the video shrinks when the trapped gas particles slow down with the addition of extremely cold nitrogen. The temperature of any [physical system](#) is related to the motions of the particles (molecules and atoms) which make up the [gas] system.<sup>[11]</sup> In [statistical mechanics](#), temperature is the measure of the average kinetic energy stored in a particle. The methods of storing this energy are dictated by the [degrees of freedom](#) of the particle itself ([energy modes](#)). Kinetic energy added ([endothermic](#) process) to gas particles by way of collisions produces linear, rotational, and vibrational motion. In contrast, a molecule in a solid can only increase its vibrational modes with the addition of heat as the lattice crystal structure prevents both linear and rotational motions. These heated gas molecules have a greater speed range which constantly varies due to constant collisions with other particles. The speed range can be described by the [Maxwell-Boltzmann distribution](#). Use of this distribution implies [ideal gases](#) near [thermodynamic equilibrium](#) for the system of particles being considered.

## Specific volume

*Main article:* [Specific volume](#)

The symbol used to represent *specific volume* in equations is "**v**" with SI units of cubic meters per kilogram.

*See also:* [Gas volume](#)

The symbol used to represent **volume** in equations is "**V**" with SI units of cubic meters.

When performing a [thermodynamic](#) analysis, it is typical to speak of [intensive and extensive properties](#). Properties which depend on the amount of gas (either by mass or volume) are called *extensive* properties, while properties that do not depend on the amount of gas are called *intensive* properties. **Specific volume** is an example of an *intensive* property because it is the ratio of volume occupied by a *unit of mass* of a gas that is identical throughout a system at equilibrium.<sup>[12]</sup> 1000 atoms a gas occupy the same space as any other 1000 atoms for any given temperature and pressure. This concept is easier to visualize for solids such as [iron](#) which are [incompressible](#) compared to gases. Since a gas fills any container in which it is placed, **volume** is an *extensive property*.

## Density

*Main article:* [Density](#)

The symbol used to represent **density** in equations is **ρ** (rho) with SI units of kilograms per cubic meter. This term is the [reciprocal](#) of specific volume.

Since gas molecules can move freely within a container, their mass is normally characterized by **density**. Density is the amount of mass per unit volume of a substance, or the inverse of specific volume. For gases, the density can vary over a wide range because the particles are free to move closer together when constrained by pressure or volume. This variation of density is referred to as [compressibility](#). Like pressure and temperature, density is a [state variable](#) of a gas and the change in density during any process is governed by the laws of thermodynamics. For a [static gas](#), the density is the same throughout the entire container.

Density is therefore a [scalar quantity](#). It can be shown by **kinetic theory** that the density is *inversely* proportional to the size of the container in which a fixed mass of gas is confined. In this case of a fixed mass, the density decreases as the volume increases.

## Microscopic

If one could observe a gas under a powerful microscope, one would see a collection of particles (molecules, atoms, ions, electrons, etc.) without any definite shape or volume that are in more or less random motion. These neutral gas particles only change direction when they collide with another particle or with the sides of the container. In an ideal gas, these collisions are perfectly elastic. This particle or [microscopic](#) view of a gas is described by the [Kinetic-molecular theory](#). The assumptions behind this theory can be found in the postulates section of [Kinetic Theory](#).

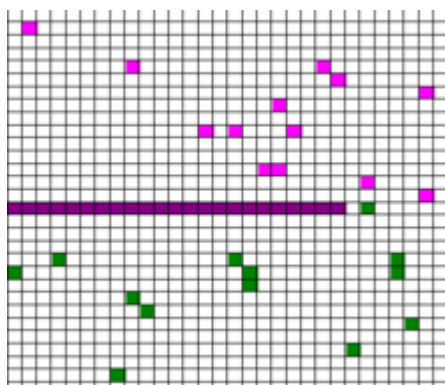
### Kinetic theory

*Main article: [Kinetic theory](#)*

**Kinetic theory** provides insight into the macroscopic properties of gases by considering their molecular composition and motion. Starting with the definitions of [momentum](#) and [kinetic energy](#),<sup>[13]</sup> one can use the [conservation of momentum](#) and geometric relationships of a cube to relate macroscopic system properties of temperature and pressure to the microscopic property of kinetic energy per molecule. The theory provides averaged values for these two properties.

The theory also explains how the gas system responds to change. For example, as a gas is heated from absolute zero, when it is (in theory) perfectly still, its [internal energy](#) (temperature) is increased. As a gas is heated, the particles speed up and its temperature rises. This results in greater numbers of collisions with the container per unit time due to the higher particle speeds associated with elevated temperatures. The pressure increases in proportion to the number of collisions per unit time.

### Brownian motion



Random motion of gas particles results in [diffusion](#).

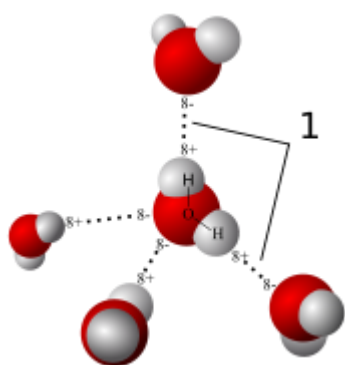
*Main article: [Brownian motion](#)*



Brownian motion is the mathematical model used to describe the random movement of particles suspended in a fluid. The gas particle animation, using pink and green particles, illustrates how this behavior results in the spreading out of gases ([entropy](#)). These events are also described by [particle theory](#).

Since it is at the limit of (or beyond) current technology to observe individual gas particles (atoms or molecules), only theoretical calculations give suggestions about how they move, but their motion is different from Brownian motion because Brownian motion involves a smooth drag due to the frictional force of many gas molecules, punctuated by violent collisions of an individual (or several) gas molecule(s) with the particle. The particle (generally consisting of millions or billions of atoms) thus moves in a jagged course, yet not so jagged as would be expected if an individual gas molecule were examined.

## Intermolecular forces



When gases are compressed, intermolecular forces like those shown here start to play a more active role.

Main articles: [van der Waals force](#) and [Intermolecular force](#)

As discussed earlier, momentary attractions (or repulsions) between particles have an effect on [gas dynamics](#). In [physical chemistry](#), the name given to these intermolecular forces is *van der Waals force*. These forces play a key role in determining [physical properties](#) of a gas such as [viscosity](#) and [flow rate](#) (see physical characteristics section). Ignoring these forces in certain conditions (see [Kinetic-molecular theory](#)) allows a [real gas](#) to be treated like an [ideal gas](#). This assumption allows the use of [ideal gas laws](#) which greatly simplifies calculations.

Proper use of these gas relationships requires the [Kinetic-molecular theory](#) (KMT). When gas particles possess a magnetic charge or [Intermolecular force](#) they gradually influence one another as the spacing between them is reduced (the hydrogen bond model illustrates one example). In the absence of any charge, at some point when the spacing between gas particles is greatly reduced they can no longer avoid collisions between themselves at normal gas temperatures. Another case for increased collisions among gas particles would include a fixed volume of gas, which upon heating would contain very fast particles. *This means that these ideal equations provide reasonable results except for extremely high pressure (compressible) or high temperature (ionized) conditions.* Notice that all of these excepted conditions allow energy transfer to take place within the gas system. The absence of these internal transfers is what is referred to as ideal conditions in which the energy exchange occurs only at the boundaries of the system. Real gases experience some of these collisions and intermolecular forces. When these collisions are statistically negligible (incompressible), results from these

ideal equations are still meaningful. If the gas particles are compressed into close proximity they behave more like a liquid (see [fluid dynamics](#)).

## Simplified models

*Main article:* [Equation of state](#)

An *equation of state* (for gases) is a mathematical model used to roughly describe or predict the state properties of a gas. At present, there is no single equation of state that accurately predicts the properties of all gases under all conditions. Therefore, a number of much more accurate equations of state have been developed for gases in specific temperature and pressure ranges. The "gas models" that are most widely discussed are "perfect gas", "ideal gas" and "real gas". Each of these models has its own set of assumptions to facilitate the analysis of a given thermodynamic system.<sup>[14]</sup> Each successive model expands the temperature range of coverage to which it applies.

### Ideal and perfect gas models

*Main article:* [Perfect gas](#)

The [equation of state](#) for an ideal or perfect gas is the [ideal gas law](#) and reads

$$PV = nRT,$$

where  $P$  is the pressure,  $V$  is the volume,  $n$  is amount of gas (in mol units),  $R$  is the [universal gas constant](#), 8.314 J/(mol K), and  $T$  is the temperature. Written this way, it is sometimes called the "chemist's version", since it emphasizes the number of molecules  $n$ . It can also be written as

$$P = \rho R_s T,$$

where  $R_s$  is the specific gas constant for a particular gas, in units J/(kg K), and  $\rho = m/V$  is density. This notation is the "gas dynamicist's" version, which is more practical in modeling of gas flows involving acceleration without chemical reactions.

The ideal gas law does not make an assumption about the specific heat of a gas. In the most general case, the specific heat is a function of both temperature and pressure. If the pressure-dependence is neglected (and possibly the temperature-dependence as well) in a particular application, sometimes the gas is said to be a [perfect gas](#), although the exact assumptions may vary depending on the author and/or field of science.

For an ideal gas, the ideal gas law applies without restrictions on the specific heat. An ideal gas is a simplified "real gas" with the assumption that the [compressibility factor](#)  $Z$  is set to 1 meaning that this pneumatic ratio remains constant. A compressibility factor of one also requires the four state variables to follow the [ideal gas law](#).

This approximation is more suitable for applications in engineering although simpler models can be used to produce a "ball-park" range as to where the real solution should lie. An example where the "ideal gas approximation" would be suitable would be inside a

[combustion chamber](#) of a [jet engine](#).<sup>[15]</sup> It may also be useful to keep the elementary reactions and chemical dissociations for calculating [emissions](#).

## Real gas



21 April 1990 eruption of [Mount Redoubt, Alaska](#), illustrating real gases not in thermodynamic equilibrium.

*Main article:* [Real gas](#)

Each one of the assumptions listed below adds to the complexity of the problem's solution. As the density of a gas increases with pressure rises, the intermolecular forces play a more substantial role in gas behavior which results in the ideal gas law no longer providing "reasonable" results. At the upper end of the engine temperature ranges (e.g. combustor sections – 1300 K), the complex fuel particles absorb internal energy by means of rotations and vibrations that cause their specific heats to vary from those of diatomic molecules and noble gases. At more than double that temperature, electronic excitation and dissociation of the gas particles begins to occur causing the pressure to adjust to a greater number of particles (transition from gas to [plasma](#)).<sup>[16]</sup> Finally, all of the thermodynamic processes were presumed to describe uniform gases whose velocities varied according to a fixed distribution. Using a non-equilibrium situation implies the flow field must be characterized in some manner to enable a solution. One of the first attempts to expand the boundaries of the ideal gas law was to include coverage for different [thermodynamic processes](#) by adjusting the equation to read  $pV^n = \text{constant}$  and then varying the  $n$  through different values such as the [specific heat ratio](#),  $\gamma$ .

**Real gas effects** include those adjustments made to account for a greater range of gas behavior:

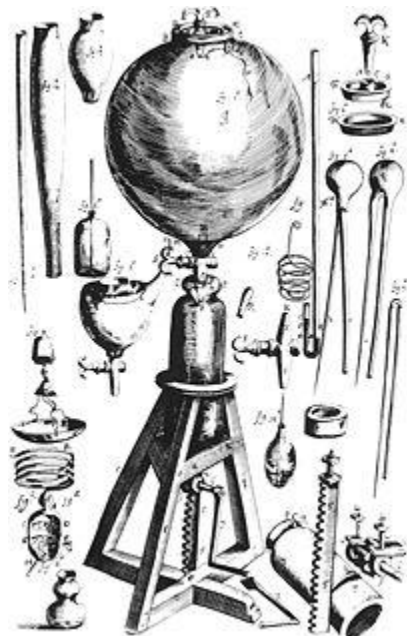
- [Compressibility effects](#) ( $Z$  allowed to vary from 1.0)
- Variable [heat capacity](#) (specific heats vary with temperature)
- Van der Waals forces (related to compressibility, can substitute other equations of state)
- [Non-equilibrium thermodynamic effects](#)
- Issues with molecular [dissociation](#) and [elementary reactions](#) with variable composition.

For most applications, such a detailed analysis is excessive. Examples where "Real Gas effects" would have a significant impact would be on the [Space Shuttle re-entry](#) where extremely high temperatures and pressures are present or the gases produced during geological events as in the image of the 1990 eruption of [Mount Redoubt](#).

# Historical synthesis

## Boyle's law

See also: [Gas laws](#)



Boyle's equipment.

Main article: [Boyle's law](#)

Boyle's Law was perhaps the first expression of an equation of state. In 1662 [Robert Boyle](#) performed a series of experiments employing a J-shaped glass tube, which was sealed on one end. Mercury was added to the tube, trapping a fixed quantity of air in the short, sealed end of the tube. Then the volume of gas was carefully measured as additional mercury was added to the tube. The pressure of the gas could be determined by the difference between the mercury level in the short end of the tube and that in the long, open end. Through these experiments, Boyle noted that the *gas volume varied inversely with the pressure*.<sup>[17]</sup> The image of Boyle's Equipment shows some of the exotic tools used by Boyle during his study of gases.

- **Boyle's Law** – describes a gas in which the number of particles and Temperature are constant.
- $PV = \text{constant}$  in this situation  $\text{constant} = nRT$  from the ideal gas law.

## Law of volumes

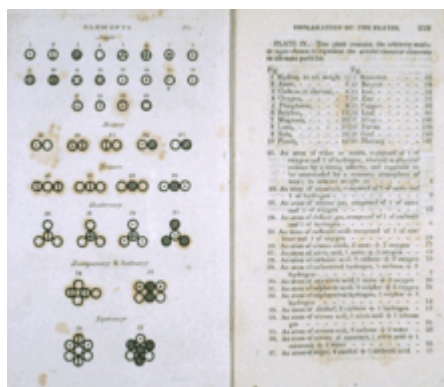
Main articles: [Charles's law](#) and [Gay-Lussac's Law](#)

In 1787, the French physicist and balloon pioneer, [Jacques Charles](#), found that oxygen, nitrogen, hydrogen, carbon dioxide, and air expand to the same extent over the same 80 kelvin interval.

In 1802, [Joseph Louis Gay-Lussac](#) published results of similar, though more extensive experiments, indicating a linear relationship between volume and temperature. Gay-Lussac credited Charles's earlier work by naming the law in his honor. In the absence of this linkage, Dalton could have been in contention for this honor for his previously published work on partial pressures.

- **Law of Volumes** – Both Charles and Gay-Lussac played a role in developing this relationship. <sup>[18]</sup>
- $V/T = \text{constant}$  – notice that  $\text{constant} = nR/P$  from the ideal gas law.

## Avogadro's law



[Dalton's notation](#).

Main article: [Avogadro's law](#)

In 1811, Amedeo Avogadro verified that equal volumes of pure gases contain the same number of particles. His theory was not generally accepted until 1858 when another Italian chemist Stanislao Cannizzaro was able to explain non-ideal exceptions. For his work with gases a century prior, the number that bears his name [Avogadro's constant](#) represents the number of atoms found in 12 grams of elemental carbon-12 ( $6.022 \times 10^{23} \text{ mol}^{-1}$ ). This specific number of gas particles, at standard temperature and pressure (ideal gas law) occupies 22.40 liters, which is referred to as the [molar volume](#).

- **Avogadro's Law** – describes a gas in a container in which the pressure and temperature are constant. The simplified form for the ideal gas law follows:
- $V/n = \text{constant}$  – notice that  $\text{constant} = RT/P$  from the ideal gas law.

## Dalton's law

Main article: [Dalton's law](#)

In 1801, [John Dalton](#) published the **Law of Partial Pressures** from his work with ideal gas law relationship: The pressure of a mixture of gases is equal to the sum of the pressures of all of the constituent gases alone. Mathematically, this can be represented for  $n$  species as:

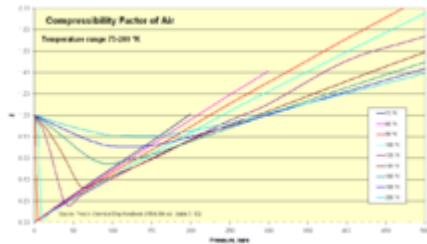
$$Pressure_{total} = Pressure_1 + Pressure_2 + \dots + Pressure_n$$

The image of Dalton's journal depicts symbology he used as shorthand to record the path he followed. Among his key journal observations upon mixing unreactive "elastic fluids" (gases) were the following.<sup>[19]</sup>:

- Unlike liquids, heavier gases did not drift to the bottom upon mixing.
- Gas particle identity played no role in determining final pressure (they behaved as if their size was negligible).

## Special topics

### Compressibility



Compressibility factors for air.

Main article: [Compressibility factor](#)

Thermodynamicists use this factor ( $Z$ ) to alter the ideal gas equation to account for compressibility effects of real gases. This factor represents the ratio of actual to ideal specific volumes. It is sometimes referred to as a "fudge-factor" or correction to expand the useful range of the ideal gas law for design purposes. *Usually* this  $Z$  value is very close to unity. The compressibility factor image illustrates how  $Z$  varies over a range of very cold temperatures.

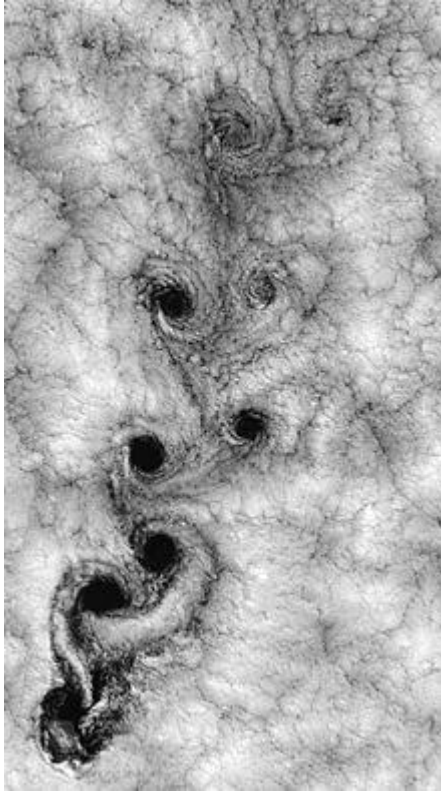
### Reynolds number

Main article: [Reynolds number](#)

In fluid mechanics, the Reynolds number is the ratio of inertial forces ( $v_s\rho$ ) to viscous forces ( $\mu/L$ ). It is one of the most important dimensionless numbers in fluid dynamics and is used, usually along with other dimensionless numbers, to provide a criterion for determining dynamic similitude. As such, the Reynolds number provides the link between modeling results (design) and the full-scale actual conditions. It can also be used to characterize the flow.

### Viscosity



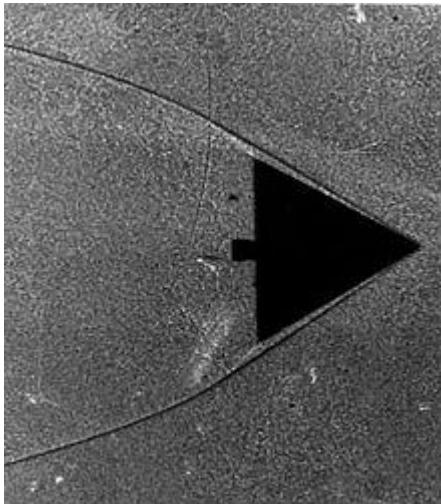


Satellite view of weather pattern in vicinity of [Robinson Crusoe Islands](#) on 15 September 1999, shows a unique turbulent cloud pattern called a [Kármán vortex street](#)

*Main article:* [Viscosity](#)

Viscosity, a physical property, is a measure of how well adjacent molecules stick to one another. A solid can withstand a shearing force due to the strength of these sticky intermolecular forces. A fluid will continuously deform when subjected to a similar load. While a gas has a lower value of viscosity than a liquid, it is still an observable property. If gases had no viscosity, then they would not stick to the surface of a wing and form a boundary layer. A study of the [delta wing](#) in the [Schlieren](#) image reveals that the gas particles stick to one another (see Boundary layer section).

## Turbulence





[Delta wing](#) in wind tunnel. The shadows form as the indices of refraction change within the gas as it compresses on the leading edge of this wing.

*Main article:* [Turbulence](#)

In fluid dynamics, **turbulence** or turbulent flow is a flow regime characterized by chaotic, stochastic property changes. This includes low momentum diffusion, high momentum convection, and rapid variation of pressure and velocity in space and time. The Satellite view of weather around Robinson Crusoe Islands illustrates just one example.

## Boundary layer

*Main article:* [Boundary layer](#)

Particles will, in effect, "stick" to the surface of an object moving through it. This layer of particles is called the **boundary layer**. At the surface of the object, it is essentially static due to the friction of the surface. The object, with its boundary layer is effectively the new shape of the object that the rest of the molecules "see" as the object approaches. This boundary layer *can* separate from the surface, essentially creating a new surface and completely changing the flow path. The classical example of this is a [stalling airfoil](#). The delta wing image clearly shows the boundary layer thickening as the gas flows from right to left along the leading edge.

## Maximum entropy principle

*Main article:* [Principle of maximum entropy](#)

As the total number of degrees of freedom approaches infinity, the system will be found in the [macrostate](#) that corresponds to the highest [multiplicity](#). In order to illustrate this principle, observe the skin temperature of a frozen metal bar. Using a thermal image of the skin temperature, note the temperature distribution on the surface. This initial observation of temperature represents a "[microstate](#)." At some future time, a second observation of the skin temperature produces a second microstate. By continuing this observation process, it is possible to produce a series of microstates that illustrate the thermal history of the bar's surface. Characterization of this historical series of microstates is possible by choosing the macrostate that successfully classifies them all into a single grouping.

## Thermodynamic equilibrium

*Main article:* [Thermodynamic equilibrium](#)

When energy transfer ceases from a system, this condition is referred to as thermodynamic equilibrium. Usually this condition implies the system and surroundings are at the same temperature so that heat no longer transfers between them. It also implies that external forces are balanced (volume does not change), and all chemical reactions within the system are complete. The timeline varies for these events depending on the system in question. A container of ice allowed to melt at room temperature takes hours, while in semiconductors the heat transfer that occurs in the device transition from an on to off state could be on the order of a few nanoseconds.



## See also

- [Air conditioning](#)
- [Argon](#)
- [Atmosphere](#)
- [Bellows](#)
- [Breath](#)
- [Carbon Dioxide](#)
- [Cavendish, Henry](#)
- [Chlorine](#)
- [Clouds](#)
- [Cooking](#)
- [Electrolysis](#)
- [Flame tests](#)
- [Kites](#)
- [Lavoisier, Antoine](#)
- [Lift \(soaring\)](#)
- [Lighting](#)
- [Lightning](#)
- [List of plasma \(physics\) articles](#)
- [Liquid](#)
- [Lung](#)
- [Mixmaster dynamics](#)
- [Nitrogen](#)
- [Odor](#)
- [Oxygen](#)
- [Parachute](#)
- [Petroleum](#)
- [Plasma \(physics\)](#)
- [Priestley, Joseph](#)
- [Ramsay, William](#)
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- [Vapor](#)
- [Volcanic gas](#)
- [Weather](#)
- [Wind](#)
- [Wind mill](#)
- [Wind turbine](#)

## Notes

1. <sup>△</sup> This early 20th century discussion infers what is regarded as the plasma state. See page 137 of American Chemical Society, Faraday Society, Chemical Society (Great Britain) *The Journal of physical chemistry, Volume 11* Cornell (1907).

2.           ^ The work by T. Zelevinski provides another link to latest research about Strontium in this new field of study. See Tanya Zelevinsky (2009). "[84Sr—just right for forming a Bose-Einstein condensate](#)". *Physics 2*: 94. <http://physics.aps.org/articles/v2/94>.
3.           ^ for links material on the [Bose-Einstein condensate](#) see [Quantum Gas Microscope Offers Glimpse Of Quirky Ultracold Atoms](#). ScienceDaily. 4 November 2009.
4.           ^ J. B. van Helmont, *Ortus medicinae*. ... (Amsterdam, (Netherlands): Louis Elzevir, 1652 (first edition: 1648)). The word "gas" first appears on [page 58](#), where he mentions: "... Gas (meum scilicet inventum) ..." (... gas (namely, my discovery) ...). On [page 59](#), he states: "... in nominis egestate, halitum illum, Gas vocavi, non longe a Chao ..." (... in need of a name, I called this vapor "gas", not far from "chaos" ...)
5.           ^ Harper, Douglas. "[gas](#)". *Online Etymology Dictionary*. <http://www.etymonline.com/index.php?term=gas>.
6.           ^ The authors make the connection between molecular forces of metals and their corresponding physical properties. By extension, this concept would apply to gases as well, though not universally. Cornell (1907) pp. 164–5.
7.           ^ One noticeable exception to this physical property connection is conductivity which varies depending on the state of matter (ionic compounds in water) as described by [Michael Faraday](#) in the 1833 when he noted that ice does not conduct a current. See page 45 of John Tyndall's *Faraday as a Discoverer* (1868).
8.           ^ John S. Hutchinson (2008). *Concept Development Studies in Chemistry*. p. 67. <http://cnx.org/content/col110264/latest/>.
9.           ^ Anderson, p.501
10.          ^ J. Clerk Maxwell (1904). *Theory of Heat*. Mineola: Dover Publications. pp. 319–20. [ISBN 0-486-41735-2](#).
11.          ^ See pages 137–8 of Society, Cornell (1907).
12.          ^ Kenneth Wark (1977). *Thermodynamics* (3 ed.). McGraw-Hill. p. 12. [ISBN 0-07-068280-1](#).
13.          ^ For assumptions of Kinetic Theory see McPherson, pp.60–61
14.          ^ Anderson, pp. 289–291
15.          ^ John, p.205
16.          ^ John, pp. 247–56
17.          ^ McPherson, pp.52–55
18.          ^ McPherson, pp.55–60
19.          ^ John P. Millington (1906). *John Dalton*. pp. 72, 77–78.

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## Further reading

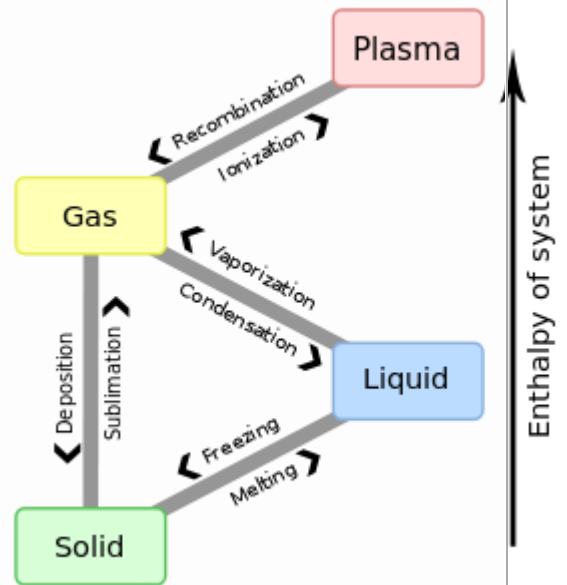
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### States of matter (classic)

<p><b>State</b></p>	<ul style="list-style-type: none"> <li>• <a href="#">Solid</a> •</li> <li>• <a href="#">Liquid</a> •</li> <li>• <b>Gas</b> / <a href="#">Vapor</a> •</li> <li>• <a href="#">Plasma</a></li> </ul>
<p><b>Low energy</b></p>	<ul style="list-style-type: none"> <li>• <a href="#">Bose–Einstein condensate</a> •</li> <li>• <a href="#">Fermionic condensate</a> •</li> <li>• <a href="#">Degenerate matter</a> •</li> <li>• <a href="#">Quantum Hall</a> •</li> <li>• <a href="#">Rydberg matter</a> •</li> <li>• <a href="#">Strange matter</a> •</li> <li>• <a href="#">Superfluid</a> •</li> <li>• <a href="#">Supersolid</a></li> </ul>
<p><b>High energy</b></p>	<ul style="list-style-type: none"> <li>• <a href="#">QCD matter</a> •</li> <li>• <a href="#">Quark–gluon plasma</a> •</li> <li>• <a href="#">Supercritical fluid</a></li> </ul>
<p><b>Other states</b></p>	<ul style="list-style-type: none"> <li>• <a href="#">Colloid</a> •</li> <li>• <a href="#">Glass</a> •</li> <li>• <a href="#">Liquid crystal</a> •</li> <li>• Magnetically ordered</li> </ul> <p>(</p> <ul style="list-style-type: none"> <li>○ <a href="#">Antiferromagnet</a> •</li> <li>○ <a href="#">Ferrimagnet</a> •</li> </ul>



Transitions

○ [Ferromagnet](#)

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• [String-net liquid](#) ·

• [Superglass](#)

• [Boiling](#) ·

• [Boiling point](#) ·

• [Condensation](#) ·

• [Critical line](#) ·

• [Critical point](#) ·

• [Crystallization](#) ·

• [Deposition](#) ·

• [Evaporation](#) ·

• [Flash evaporation](#) ·

• [Freezing](#) ·

• [Ionization](#) ·

• [Lambda point](#) ·

• [Melting](#) ·

• [Melting point](#) ·

• [Recombination](#) ·

• [Regelation](#) ·

• [Saturated fluid](#) ·

• [Sublimation](#) ·

• [Supercooling](#) ·

• [Triple point](#) ·

• [Vaporization](#) ·

• [Vitrification](#)

## Quantities

- [Enthalpy of fusion](#) ·
- [Enthalpy of sublimation](#) ·
- [Enthalpy of vaporization](#) ·
- [Latent heat](#) ·
- [Latent internal energy](#) ·
- [Trouton's ratio](#) ·
- [Volatility](#)

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# Dielectric strength

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In [physics](#), the term **dielectric strength** has the following meanings:

- Of an insulating material, the maximum electric [field strength](#) that it can withstand intrinsically without breaking down, *i.e.*, without experiencing [failure](#) of its insulating properties.
- For a given configuration of dielectric material and electrodes, the minimum [electric field](#) that produces breakdown.
- the maximum electric stress the dielectric material can withstand without breakdown.

The theoretical [dielectric](#) strength of a material is an intrinsic property of the bulk material and is dependent on the configuration of the material or the electrodes with which the field is applied. At breakdown, the electric field frees bound electrons. If the applied electric field is sufficiently high, free electrons from [background radiation](#) may become accelerated to velocities that can liberate additional electrons during collisions with neutral atoms or molecules in a process called [avalanche breakdown](#). Breakdown occurs quite abruptly (typically in [nanoseconds](#)), resulting in the formation of an electrically conductive path and a [disruptive discharge](#) through the material. For solid materials, a breakdown event severely degrades, or even destroys, its insulating capability.

Factors affecting apparent dielectric strength

- it decreases slightly with increased sample thickness. (see "defects" below)
- it decreases with increased [operating temperature](#).
- it decreases with increased frequency.
- for gases (e.g. nitrogen, sulfur hexafluoride) it normally decreases with increased humidity.
- for air, dielectric strength increases slightly as humidity increases

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## [\[edit\]](#) Breakdown field strength

The field strength at which breakdown occurs depends on the respective geometries of the dielectric (insulator) and the electrodes with which the electric field is applied, as well as the

rate of increase at which the [electric field](#) is applied. Because dielectric materials usually contain minute defects, the practical dielectric strength will be a fraction of the intrinsic dielectric strength of an ideal, defect-free, material. Dielectric films tend to exhibit greater dielectric strength than thicker samples of the same material. For instance, the dielectric strength of silicon dioxide films of a few hundred nm to a few  $\mu\text{m}$  thick is approximately 0.5GV/m.<sup>[1]</sup> However very thin layers (below, say, 100 nm) become partially conductive because of [electron tunneling](#). Multiple layers of thin dielectric films are used where maximum practical dielectric strength is required, such as high voltage [capacitors](#) and pulse [transformers](#). Since the dielectric strength of gases varies depending on the shape and configuration of the electrodes, it is usually measured as a fraction of the dielectric strength of [Nitrogen gas](#).

Dielectric strength (in MV/m, or  $10^6$  Volt/meter) of various common materials:

Substance	Dielectric Strength (MV/m)
<a href="#">Helium</a> (relative to nitrogen) <sup>[2]</sup>	0.15
<a href="#">Air</a> <sup>[3]</sup>	3.0
<a href="#">Alumina</a> <sup>[2]</sup>	13.4
Window <a href="#">glass</a> <sup>[2]</sup>	9.8 - 13.8
<a href="#">Silicone oil</a> , <a href="#">Mineral oil</a> <sup>[2][4]</sup>	10 - 15
<a href="#">Benzene</a> <sup>[2]</sup>	163
<a href="#">Polystyrene</a> <sup>[2]</sup>	19.7
<a href="#">Polyethylene</a> <sup>[5]</sup>	18.9 - 21.7
<a href="#">Neoprene</a> rubber <sup>[2]</sup>	15.7 - 26.7
Distilled <a href="#">Water</a> <sup>[2]</sup>	65 - 70
High <a href="#">Vacuum</a> (field emission limited) <sup>[6]</sup>	20 - 40 (depends on electrode shape)
<a href="#">Fused silica</a> <sup>[7]</sup>	25–40 at 20 °C
Waxed paper <sup>[8]</sup>	40 - 60
<a href="#">PTFE</a> (Teflon, <a href="#">Extruded</a> ) <sup>[2]</sup>	19.7
<a href="#">PTFE</a> (Teflon, Insulating Film) <sup>[2][9]</sup>	60 - 173
<a href="#">Mica</a> <sup>[2]</sup>	118

## [\[edit\]](#) Units

In [SI](#), the unit of dielectric strength is [volts](#) per [meter](#) (V/m). It is also common to see related units such as [volts](#) per [centimeter](#) (V/cm), [megavolts](#) per meter (MV/m), and so on.

In [United States customary units](#), dielectric strength is often specified in volts per [mil](#) (a mil is 1/1000 [inch](#)).<sup>[10]</sup> The conversion is:

$$1 \text{ V/m} = 2.54 \times 10^{-5} \text{ V/mil}$$

$$1 \text{ V/mil} = 3.94 \times 10^4 \text{ V/m}$$

## [\[edit\]](#) See also

- [Breakdown voltage](#)
- [Relative permittivity](#)
- [Rotational Brownian motion](#)

## **[[edit](#)] References**

1. <sup>^</sup> ["Electrical insulation properties of sputter-deposited SiO<sub>2</sub>, Si<sub>3</sub>N<sub>4</sub> and Al<sub>2</sub>O<sub>3</sub> films at room temperature and 400 °C - Bartzsch - 2009 - physica status solidi \(a\) - Wiley Online Library"](#). Onlinelibrary.wiley.com. 2009-01-21. <http://onlinelibrary.wiley.com/doi/10.1002/pssa.200880481/pdf>. Retrieved 2011-11-08.
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  10. <sup>^</sup> For one of many examples, see *Polyimides: materials, processing and applications*, by A.J. Kirby, [google books link](#)
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## **[[edit](#)] External links**

### **Calculating the Dielectric Strength**

The dielectric strength is the maximum working voltage a material can withstand without breaking down.

It is normally expressed in Volts/mm. The material manufacturer should be able to supply this information but if not an approximate value can be found using a Holiday Detector.

#### *Calculating the Dielectric Strength*

1. Obtain a sample of material with a uniform thickness of about 1mm applied to a sheet of metal.
2. Connect the Holiday Detector to the sample with the earth lead connected to the metal and the high voltage probe (via a pointed probe) to the surface of the material.
3. Starting with the output voltage set to minimum, slowly increase the volts until the material breaks down and the alarm on the Holiday Detector sounds.
4. Lift the HV electrode off the surface of the material and note the output voltage.

5. Repeat this test a number of times on a new area of the sample at least 20mm from where any previous breakdowns have occurred, noting the breakdown voltage each time.
6. Take an average of the voltages and then 75% of that is approximately the dielectric strength of the material.

So now you have a value for the dielectric strength we can look at how this relates to the test voltage calculated previously.

It is important to check, before you start testing, that the test voltage you have selected is not so high that it will actually create faults in a coating. This would rather defeat the object of holiday detection. To demonstrate this let's look at a worked example.

### Example

Say we have a coating 2mm thick which has a dielectric strength of 8400 V/mm. Using the NACE formula the test voltage is:

We know the dielectric strength is 8400 V /mm so for 2mm the maximum voltage before breakdown occurs is  $2 \times 8400 = 16,800$  V. In this example then the test voltage of 11,180 V can be used since it is less than the breakdown voltage of the material (16,800V).

So what if the dielectric strength is below the calculated test voltage. Let's look at the same example as was shown above, a coating 2mm thick but this time it has a dielectric strength of 5000 V /mm. Again the test voltage is calculated to be 11,180 V but now the breakdown voltage of the material is 10,000 Volts ( $2 \times 5000$ ). This is clearly less than our test voltage and attempting to use 11,180V to test this coating would result in the creation of more holes.

In this instance high voltage holiday detection may still be used to locate flaws in the coating, but some further testing is required to ensure that this method is valid.

Referring to the example above of a 2mm coating with a dielectric strength of 5000 V / mm, the validation test would be as follows:

1. Make a small hole in a test piece.
2. With the electrode over the hole slowly increase the voltage until the spark jumps the gap. Note the voltage (which in this instance, on a 2mm coating, would be ~ 5000 V).
3. To determine the test voltage, use a value midway between the test voltage calculated using the NACE formula (in this case 11,180 V) and the minimum voltage determined from the above test (~5000V). This works out to be 8090 V.  $((11,180 - 5000) / 2) + 5000$ .
4. Now make some more holes in the test piece (making sure there is more than 20mm between each hole), this time at angles, and using your test voltage (in our example 8090V) ensure that it is possible to locate the faults.

This method of finding the test voltage is fine if all you are looking for is cracks in the coating (that is complete faults that go all the way through the coating to the substrate). Indeed, many standards only require this type of fault to be detected. However, with

careful selection of the test voltage, it is possible to find a variety of different flaws. See [A guide to using DC Holiday detectors](#) for more information.

# Electrical conductor

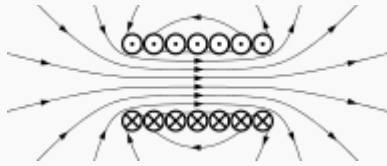
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Overhead conductors carry electric power from generating stations to customers.

In [physics](#) and [electrical engineering](#), a **conductor** is an object or type of material which permits the flow of [electric charges](#) in one or more directions. For example, an insulated [wire](#) is an electrical conductor as it can carry electricity along its length (but not across its width).

In [metallic](#) conductive materials such as [copper](#) or [aluminum](#), the movable charged particles are [electrons](#) (see [electrical conduction](#)). Positive charges may also be mobile, such as the cationic [electrolyte](#)(s) of a [battery](#), or the mobile protons of the [proton conductor](#) of a fuel cell. [Insulators](#) are non-conducting materials with few mobile charges and which support only insignificant [electric currents](#).

## Semiconductor

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*For information on devices using semiconductors and their history, see [semiconductor device](#). For other uses, see [Semiconductor \(disambiguation\)](#).*



This article **may be too [technical](#) for most readers to understand**. Please help [improve](#) this article to [make it understandable to non-experts](#), without removing the technical details. The [talk page](#) may contain suggestions. *(August 2011)*

A **semiconductor** is a material which has [electrical conductivity](#) between that of a [conductor](#) such as copper and an [insulator](#) such as glass. The conductivity of a semiconductor increases with increasing temperature, behaviour opposite to that of a metal.<sup>[1]</sup> Semiconductors can display a range of useful properties

## Photovoltaics

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[Nellis Solar Power Plant](#) at Nellis Air Force Base in the USA. These panels track the sun in one axis.



Photovoltaic SUDI shade is an autonomous and mobile station in France that replenishes energy for electric vehicles using solar energy.



Solar panels on the [International Space Station](#)

**Photovoltaics (PV)** is a method of [generating electrical power](#) by converting [solar radiation](#) into [direct current electricity](#) using [semiconductors](#) that exhibit the [photovoltaic effect](#). Photovoltaic power generation employs [solar panels](#) composed of a number of [solar cells](#) containing a photovoltaic material. Materials presently used for photovoltaics include [monocrystalline silicon](#), [polycrystalline silicon](#), [amorphous silicon](#), [cadmium telluride](#), and [copper indium gallium selenide/sulfide](#). Due to the increase demand for [renewable energy](#) sources, the manufacturing of solar cells and [photovoltaic arrays](#) has advanced considerably in recent years.

Solar photovoltaics have long been argued to be a [sustainable](#) energy source.<sup>[1]</sup> By the end of 2011, a total of 67.4 GW had been installed, sufficient to generate 85 TWh/year.<sup>[2]</sup> And by end of 2012, the 100GW installed capacity milestone was achieved.<sup>[3]</sup> Solar photovoltaics is now, after hydro and wind power, the third most important renewable energy source in terms of globally installed capacity. More than 100 countries use solar PV. Installations may be ground-mounted (and sometimes integrated with farming and grazing) or built into the roof or walls of a building (either [building-integrated photovoltaics](#) or simply rooftop).

Driven by advances in technology and increases in manufacturing

# DIELECTRIC STRENGTH OF INSULATING MATERIALS

L. I. Berger

The loss of the dielectric properties by a sample of a gaseous, liquid, or solid insulator as a result of application to the sample of an electric field\* greater than a certain critical magnitude is called *dielectric breakdown*. The critical magnitude of electric field at which the breakdown of a material takes place is called the *dielectric strength* of the material (or *breakdown voltage*). The dielectric strength of a material depends on the specimen thickness (as a rule, thin films have greater dielectric strength than that of thicker samples of a material), the electrode shape\*\*, the rate of the applied voltage increase, the shape of the voltage vs. time curve, and the medium surrounding the sample, e.g., air or other gas (or a liquid — for solid materials only).

## Breakdown in Gases

The current carriers in gases are free electrons and ions generated by external radiation. The equilibrium concentration of these particles at normal pressure is about  $10^3 \text{ cm}^{-3}$ , and hence the electrical conductivity is very small, of the order of  $10^{-16} - 10^{-15} \text{ S/cm}$ . But in a strong electric field, these particles acquire kinetic energy along their free pass, large enough to ionize the gas molecules. The new charged particles ionize more molecules; this avalanche-like process leads to formation between the electrodes of channels of conducting plasma (streamers), and the electrical resistance of the space between the electrodes decreases virtually to zero.

Because the dielectric strength (breakdown voltage) of gases strongly depends on the electrode geometry and surface condition and the gas pressure, it is generally accepted to present the data for a particular gas as a fraction of the dielectric strength of either nitrogen or sulfur hexafluoride measured at the same conditions. In Table 1, the data are presented in comparison with the dielectric strength of nitrogen, which is considered equal to 1.00. For convenience to the reader, a few average magnitudes of the dielectric strength of some gases are expressed in kilovolts per millimeter. The data in the table relate to the standard conditions, unless indicated otherwise.

## Breakdown in Liquids

If a liquid is pure, the breakdown mechanism in it is similar to that in gases. If a liquid contains liquid impurities in the form of small drops with greater dielectric constant than that of the main liquid, the breakdown is the result of formation of ellipsoids from these drops by the electric field. In a strong enough electric field, these ellipsoids merge and form a high-conductivity channel between the electrodes. The current increases the temperature in the channel, liquid boils, and the current along the steam canal leads to breakdown. Formation of a conductive channel (bridge) between the electrodes is observed also in liquids with solid impurities. If a liquid contains gas impurities in the form of small bubbles, breakdown is the result of heating of the liquid in strong electric fields. In the locations with the highest current density, the liquid boils, the size of the gas bubbles increases, they merge and form gaseous channels between the electrodes, and the breakdown medium is again the gas plasma.

## Breakdown in Solids

It is known that the current in solid insulators does not obey Ohm's law in strong electric fields. The current density increases almost exponentially with the electric field, and at a certain field magnitude it jumps to very high magnitudes at which a specimen of a material is destroyed. The two known kinds of electric breakdown are thermal and electrical breakdowns. The former is the result of material heating by the electric current. Destruction of a sample of a material happens when, at a certain voltage, the amount of heat produced by the current exceeds the heat release through the sample surface; the breakdown voltage in this case is proportional to the square root of the ratio of the thermal conductivity and electrical conductivity of the material. The electrical breakdown results from the tunneling of the charge carriers from electrodes or from the valence band or from the impurity levels into the conduction band, or by the impact ionization. The tunnel effect breakdown happens mainly in thin layers, e.g., in thin p-n junctions. Otherwise, the impact ionization mechanism dominates. For this mechanism, the dielectric strength of an insulator can be estimated using Boltzmann's kinetic equation for electrons in a crystal.

In the following tables, the dielectric strength values are for room temperature and normal atmospheric pressure, unless indicated otherwise.

\* The unit of electric field in the SI system is newton per coulomb or volt per meter.

\*\* For example, the U.S. standard ASTM D149 is based on use of symmetrical electrodes, while per U.K. standard BS2918 one electrode is a plane and the other is a rod with the axis normal to the plane.

**Table 1**  
**Dielectric Strength of Gases**

<b>Material</b>	<b>Dielectric* Strength</b>	<b>Ref.</b>	<b>Material</b>	<b>Dielectric* Strength</b>	<b>Ref.</b>
Nitrogen, N <sub>2</sub>	1.00		Trichlorofluoromethane, CCl <sub>3</sub> F	3.50	1
Hydrogen, H <sub>2</sub>	0.50	1,2		4.53	2
Helium, He	0.15	1	Trichloromethane, CHCl <sub>3</sub>	4.2	1
Oxygen, O <sub>2</sub>	0.92	2		4.39	2
Air	0.97	6	Methylamine, CH <sub>3</sub> NH <sub>2</sub>	0.81	1
Air (flat electrodes), kV/mm	3.0	3	Difluoromethane, CH <sub>2</sub> F <sub>2</sub>	0.79	2
Air, kV/mm	0.4-0.7	4	Trifluoromethane, CHF <sub>3</sub>	0.71	2
Air, kV/mm	1.40	5	Bromochlorodifluoromethane, CF <sub>2</sub> ClBr	3.84	2
Neon, Ne	0.25	1	Chlorodifluoromethane, CHClF <sub>2</sub>	1.40	1
	0.16	2		1.11	2
Argon, Ar	0.18	2	Dichlorofluoromethane, CHCl <sub>2</sub> F	1.33	1
Chlorine, Cl <sub>2</sub>	1.55	1		2.61	2
Carbon monoxide, CO	1.02	1	Chlorofluoromethane, CH <sub>2</sub> ClF	1.03	1
	1.05	2	Hexafluoroethane, C <sub>2</sub> F <sub>6</sub>	1.82	1
Carbon dioxide, CO <sub>2</sub>	0.88	1		2.55	2
	0.82	2	Ethyne (Acetylene), C <sub>2</sub> H <sub>2</sub>	1.10	1
	0.84	6		1.11	2
Nitrous oxide, N <sub>2</sub> O	1.24	2	Chloropentafluoroethane, C <sub>2</sub> ClF <sub>5</sub>	2.3	1
Sulfur dioxide, SO <sub>2</sub>	2.63	2		3.0	6
	2.68	6	Dichlorotetrafluoroethane, C <sub>2</sub> Cl <sub>2</sub> F <sub>4</sub>	2.52	1
Sulfur monochloride, S <sub>2</sub> Cl <sub>2</sub>	1.02	1	Chlorotrifluoroethylene, C <sub>2</sub> ClF <sub>3</sub>	1.82	2
(at 12.5 Torr)			1,1,1-Trichloro-2,2,2-trifluoroethane	6.55	2
Thionyl fluoride, SOF <sub>2</sub>	2.50	1	1,1,2-Trichloro-1,2,2-trifluoroethane	6.05	2
Sulfur hexafluoride, SF <sub>6</sub>	2.50	1	Chloroethane, C <sub>2</sub> H <sub>5</sub> Cl	1.00	1
	2.63	2	1,1-Dichloroethane	2.66	2
Sulfur hexafluoride, SF <sub>6</sub> , kV/mm	8.50	7	Trifluoroacetonitrile, CF <sub>3</sub> CN	3.5	1
	9.8	8	Acetonitrile, CH <sub>3</sub> CN	2.11	2
Perchloryl fluoride, ClO <sub>3</sub> F	2.73	1	Dimethylamine, (CH <sub>3</sub> ) <sub>2</sub> NH	1.04	1
Tetrachloromethane, CCl <sub>4</sub>	6.33	1	Ethylamine, C <sub>2</sub> H <sub>5</sub> NH <sub>2</sub>	1.01	1
	6.21	2	Ethylene oxide (oxirane), CH <sub>3</sub> CHO	1.01	1
Tetrafluoromethane, CF <sub>4</sub>	1.01	1	Perfluoropropene, C <sub>3</sub> F <sub>6</sub>	2.55	2
Methane, CH <sub>4</sub>	1.00	1	Octafluoropropane, C <sub>3</sub> F <sub>8</sub>	2.19	1
	1.13	2		2.47	2
Bromotrifluoromethane, CF <sub>3</sub> Br	1.35	1	3,3,3-Trifluoro-1-propene, CH <sub>2</sub> CHCF <sub>3</sub>	2.11	2
	1.97	2	Pentafluoroisocycanoethane, C <sub>2</sub> F <sub>5</sub> NC	4.5	1
Bromomethane, CH <sub>3</sub> Br	0.71	2	1,1,1,4,4,4-Hexafluoro-2-butyne, CF <sub>3</sub> CCCF <sub>3</sub>	5.84	2
Chloromethane, CH <sub>3</sub> Cl	1.29	2	Octafluorocyclobutane, C <sub>4</sub> F <sub>8</sub>	3.34	2
Iodomethane, CH <sub>3</sub> I	3.02	2	1,1,1,2,3,4,4,4-Octafluoro-2-butene	2.8	1
Iodomethane, CH <sub>3</sub> I, at 370 Torr	2.20	7	Decafluorobutane, C <sub>4</sub> F <sub>10</sub>	3.08	1
Dichloromethane, CH <sub>2</sub> Cl <sub>2</sub>	1.92	2	Perfluorobutanenitrile, C <sub>3</sub> F <sub>7</sub> CN	5.5	1
Dichlorodifluoromethane, CCl <sub>2</sub> F <sub>2</sub>	2.42	1	Perfluoro-2-methyl-1,3-butadiene, C <sub>5</sub> F <sub>8</sub>	5.5	1
	2.63	2,6	Hexafluorobenzene, C <sub>6</sub> F <sub>6</sub>	2.11	2
Chlorotrifluoromethane, CClF <sub>3</sub>	1.43	1	Perfluorocyclohexane, C <sub>6</sub> F <sub>12</sub> , (saturated vapor)	6.18	2
	1.53	2			

\*Relative to nitrogen, unless units of kV/mm are indicated.

**Table 2**  
**Dielectric Strength of Liquids**

Material	Dielectric strength kV/mm	Ref.	Material	Dielectric strength kV/mm	Ref.
Helium, He, liquid, 4.2 K	10	9		20.4	15
Static	10	11		179	17,18
Dynamic	5	11	Ethylbenzene, C <sub>8</sub> H <sub>10</sub>	226	17,18
	23	12	Propylbenzene, C <sub>9</sub> H <sub>12</sub>	250	17,18
Nitrogen, N <sub>2</sub> , liquid, 77K			Isopropylbenzene, C <sub>9</sub> H <sub>12</sub>	238	17,18
Coaxial cylinder electrodes	20	10	Decane, C <sub>10</sub> H <sub>22</sub>	192	17,18
Sphere to plane electrodes	60	10	Synthetic Paraffin Mixture		
Water, H <sub>2</sub> O, distilled	65-70	13	Synfluid 2cSt PAO	29.5	37
Carbon tetrachloride, CCl <sub>4</sub>	5.5	14	Butylbenzene, C <sub>10</sub> H <sub>14</sub>	275	17,18
	16.0	15	Isobutylbenzene, C <sub>10</sub> H <sub>14</sub>	222	17,18
Hexane, C <sub>6</sub> H <sub>14</sub>	42.0	16	Silicone oils—polydimethylsiloxanes, (CH <sub>3</sub> ) <sub>3</sub> Si-O-[Si(CH <sub>3</sub> ) <sub>2</sub> ] <sub>x</sub> -O-Si(CH <sub>3</sub> ) <sub>3</sub>		
Two 2.54 cm diameter spherical electrodes, 50.8 μm space	156	17,18	Polydimethylsiloxane silicone fluid	15.4	20
Cyclohexane, C <sub>6</sub> H <sub>12</sub>	42-48	16	Dimethyl silicone	24.0	21,22
2-Methylpentane, C <sub>6</sub> H <sub>14</sub>	149	17,18	Phenylmethyl silicone	23.2	22
2,2-Dimethylbutane, C <sub>6</sub> H <sub>14</sub>	133	17,18	Silicone oil, Basilone M50	10-15	23
2,3-Dimethylbutane, C <sub>6</sub> H <sub>14</sub>	138	17,18	Mineral insulating oils	11.8	6
Benzene, C <sub>6</sub> H <sub>6</sub>	163	17,18	Polybutene oil for capacitors	13.8	6
Chlorobenzene, C <sub>6</sub> H <sub>5</sub> Cl	7.1	14	Transformer dielectric liquid	28-30	6
	18.8	15	Isopropylbiphenyl capacitor oil	23.6	6
2,2,4-Trimethylpentane, C <sub>8</sub> H <sub>18</sub>	140	17,18	Transformer oil	110.7	24
Phenylxylylethane	23.6	19	Transformer oil Agip ITE 360	9-12.6	23
Heptane, C <sub>7</sub> H <sub>16</sub>	166	17,18	Perfluorinated hydrocarbons		
2,4-Dimethylpentane, C <sub>7</sub> H <sub>16</sub>	133	17,18	Fluorinert FC 6001	8.0	23
Toluene, C <sub>6</sub> H <sub>5</sub> CH <sub>3</sub>	199	17,18	Fluorinert FC 77	10.7	23
	46	16	Perfluorinated polyethers		
	12.0	14	Galden XAD (Mol. wt. 800)	10.5	23
	20.4	15	Galden D40 (Mol. wt. 2000)	10.2	23
Octane, C <sub>8</sub> H <sub>18</sub>	16.6	14	Castor oil	65	25

**Table 3**  
**Dielectric Strength of Solids**

Material	Dielectric strength kV/mm	Ref	Material	Dielectric strength kV/mm	Ref
Sodium chloride, NaCl, crystalline	150	26	Phlogopite, amber, natural	118	6
Potassium bromide, KBr, crystalline	80	26	Fluorophlogopite, synthetic	118	6
Ceramics			Glass-bonded mica	14.0-15.7	6
Alumina (99.9% Al <sub>2</sub> O <sub>3</sub> )	13.4	6,27a	Thermoplastic Polymers		
Aluminum silicate, Al <sub>2</sub> SiO <sub>5</sub>	5.9	6	Polypropylene	23.6	6
Berillia (99% BeO)	13.8	6,27b	Amide polymer nylon 6/6, dry	23.6	6
Boron nitride, BN	37.4	6	Polyamide-imide copolymer	22.8	6
Cordierite, Mg <sub>2</sub> Al <sub>4</sub> Si <sub>5</sub> O <sub>18</sub>	7.9	6,27c	Modified polyphenylene oxide	21.7	6
Forsterite, Mg <sub>2</sub> SiO <sub>4</sub>	9.8	28	Polystyrene	19.7	6
Porcelain	35-160	26	Polymethyl methacrylate	19.7	6
Steatite, Mg <sub>3</sub> Si <sub>4</sub> O <sub>11</sub> •H <sub>2</sub> O	9.1-15.4	6	Polyetherimide	18.9	6
Titanates of Mg, Ca, Sr, Ba, and Pb	20-120	3	Amide polymer nylon 11(dry)	16.7	6
Barium titanate, glass bonded	>30	36	Polysulfone	16.7	6
Zirconia, ZrO <sub>2</sub>	11.4	29	Styrene-acrylonitrile copolymer	16.7	6
Glasses			Acrylonitrile-butadiene-styrene	16.7	6
Fused silica, SiO <sub>2</sub>	470-670	26	Polyethersulfone	15.7	6
Alkali-silicate glass	200	26	Polybutylene terephthalate	15.7	6
Standard window glass	9.8-13.8	28	Polystyrene-butadiene copolymer	15.7	6
Micas			Acetal homopolymer	15.0	6
Muscovite, ruby, natural	118	6	Acetal copolymer	15.0	6

**Table 3**  
**Dielectric Strength of Solids (continued)**

Material	Dielectric strength kV/mm	Ref.	Material	Dielectric strength kV/mm	Ref.
Polyphenylene sulfide	15.0	6	Varnishes		
Polycarbonate	15.0	6	Vacuum-pressure impregnated baking		
Acetal homopolymer resin (molding resin)	15.0	6	type solventless polyester varnish		
Acetal copolymer resin	15.0	6	Rigid, two-part	70.9	6
Thermosetting Molding Compounds			Semiflexible high-bond thixotropic	78.7	6
Glass-filled allyl	15.7	6	Rigid high-bond high-flash	68.9	6
(Type GDI-30 per MIL-M-14G)			freon-resistant		
Glass-filled epoxy, electrical grade	15.4	6	Baking type epoxy varnish		
Glass-filled phenolic	15.0	6	Solventless, rigid, low viscosity,	90.6	6
(Type GPI-100 per MIL-M-14G)			one-part		
Glass-filled alkyd/polyester	14.8	6	Solventless, semiflexible, one-part	82.7	6
(Type MAI-60 per MIL-M-14G)			Solventless, semirigid, chemical	106.3	6
Glass-filled melamine	13.4	6	resistant, low dielectric constant		
(Type MMI-30 per MIL-M-14G)			Solvable, for hermetic electric motors	181.1	6
Extrusion Compounds for High-Temperature Insulation			Polyurethane coating		
Polytetrafluoroethylene	19.7	6	Clear conformal, fast cure		
Perfluoroalkoxy polymer	21.7	6	Standard conditions	78.7	6
Fluorinated ethylene-propylene copolymer	19.7	6	Immersion conditions	47.2	6
Ethylene-tetrafluoroethylene copolymer	15.7	6	Insulating Films and Tapes		
Polyvinylidene fluoride	10.2	6	Low-density polyethylene film	300	31
Ethylene-chlorotrifluoroethylene	19.3	6	(40 μm thick)		
copolymer			Poly- <i>p</i> -xylylene film	410-590	32
Polychlorotrifluoroethylene	19.7	6	Aromatic polymer films		
Extrusion Compounds for Low-Temperature Insulation			Kapton H (Du Pont)	389-430	33
Polyvinyl chloride			Ultem (GE Plastic and Roem AG)	437-565	33
Flexible	11.8-15.7	30	Hostaphan (Hoechst AG)	338-447	33
Rigid	13.8-19.7	30	Amorphous Stabar K2000	404-422	33
Polyethylene	18.9	28	(ICI film)		
Polyethylene, low-density	21.7	6	Stabar S100 (ICI film)	353-452	33
	300	31	Polyetherimide film (26 μm)	486	34
Polyethylene, high-density	19.7	6	Parylene N/D (poly- <i>p</i> -xylylene/poly-		
Polypropylene/polyethylene copolymer	23.6	6	dichloro- <i>p</i> -xylylene) 25 μm film	275	6
Embedding Compounds			Cellulose acetate film	157	6
Basic epoxy resin:	19.7	6	Cellulose triacetate film	157	6
bisphenol-A/epichlorohydrin			Polytetrafluoroethylene film	87-173	6
polycondensate			Perfluoroalkoxy film	157-197	6
Cycloaliphatic epoxy: alicyclic	19.7	6	Fluorinated ethylene-propylene	197	6
diepoxy carboxylate			copolymer film		
Polyetherketone	18.9	30	Ethylene-tetrafluoroethylene film	197	6
Polyurethanes			Ethylene-chlorotrifluoroethylene	197	6
Two-component, polyol-cured	25.4	6	copolymer film		
Two-part solventless,	24.0	6	Polychlorotrifluoroethylene film	118-153.5	6
polybutylene-based			High-voltage rubber insulating tape	28	6
Silicones			Composites		
Clear two-part heat curing electrical	21.7	6	Isophthalic polyester (vinyl toluene		
grade silicone embedding resin			monomer) filled with		
Red insulating enamel (MIL-E-22118)			Calcium carbonate, CaCO <sub>3</sub>	15.0	38
Dry	47.2	6	Gypsum, CaSO <sub>4</sub>	14.4	38
Wet	11.8	6	Alumina trihydrate	15.4	38
Enamels			Clay	14.4	38
Red enamel, fast cure			BPA fumarate polyester (vinyl toluene		
Standard conditions	78.7	6	monomer) filled with		
Immersion conditions	47.2	6	Calcium carbonate	6.1	38
Black enamel			Gypsum	5.9	38
Standard conditions	70.9	6	Alumina trihydrate	11.8	38
Immersion conditions	47.2	6	Clay	12.6	38

**Table 3**  
**Dielectric Strength of Solids (continued)**

Material	Dielectric strength kV/mm	Ref.	Material	Dielectric strength kV/mm	Ref.
Polysulfone resin—30% glass fiber	16.5-18.7	38	Butyl rubber	23.6	6
Polyamid resin (Nylon 66)— 30% carbon fiber	13.0	38	Neoprene	15.7-27.6	6
Polyimide thermoset resin, glass reinforced	12.0	39	Silicone rubber	26-36	6
Polyester resin (thermoplastic)— 40% glass fiber	20.0	38	Room-temperature vulcanized silicone rubber	9.2-10.9	35
Epoxy resin (diglycidyl ether of bisphenol A), glass reinforced	16.0	40	Ureas (from carbamide to tetraphenylurea)	11.8-15.7	28
Various Insulators			Dielectric papers		
Rubber, natural	100-215	26	Aramid paper, calendered	28.7	6
			Aramid paper, uncalendered	12.2	6
			Aramid with Mica	39.4	6

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# DIELECTRIC STRENGTH OF INSULATING MATERIALS

L. I. Berger

The loss of the dielectric properties by a sample of a gaseous, liquid, or solid insulator as a result of application to the sample of an electric field\* greater than a certain critical magnitude is called *dielectric breakdown*. The critical magnitude of electric field at which the breakdown of a material takes place is called the *dielectric strength* of the material (or *breakdown voltage*). The dielectric strength of a material depends on the specimen thickness (as a rule, thin films have greater dielectric strength than that of thicker samples of a material), the electrode shape\*\*, the rate of the applied voltage increase, the shape of the voltage vs. time curve, and the medium surrounding the sample, e.g., air or other gas (or a liquid — for solid materials only).

## Breakdown in Gases

The current carriers in gases are free electrons and ions generated by external radiation. The equilibrium concentration of these particles at normal pressure is about  $10^3 \text{ cm}^{-3}$ , and hence the electrical conductivity is very small, of the order of  $10^{-16} - 10^{-15} \text{ S/cm}$ . But in a strong electric field, these particles acquire kinetic energy along their free pass, large enough to ionize the gas molecules. The new charged particles ionize more molecules; this avalanche-like process leads to formation between the electrodes of channels of conducting plasma (streamers), and the electrical resistance of the space between the electrodes decreases virtually to zero.

Because the dielectric strength (breakdown voltage) of gases strongly depends on the electrode geometry and surface condition and the gas pressure, it is generally accepted to present the data for a particular gas as a fraction of the dielectric strength of either nitrogen or sulfur hexafluoride measured at the same conditions. In Table 1, the data are presented in comparison with the dielectric strength of nitrogen, which is considered equal to 1.00. For convenience to the reader, a few average magnitudes of the dielectric strength of some gases are expressed in kilovolts per millimeter. The data in the table relate to the standard conditions, unless indicated otherwise.

## Breakdown in Liquids

If a liquid is pure, the breakdown mechanism in it is similar to that in gases. If a liquid contains liquid impurities in the form of small drops with greater dielectric constant than that of the main liquid, the breakdown is the result of formation of ellipsoids from these drops by the electric field. In a strong enough electric field, these ellipsoids merge and form a high-conductivity channel between the electrodes. The current increases the temperature in the channel, liquid boils, and the current along the steam canal leads to breakdown. Formation of a conductive channel (bridge) between the electrodes is observed also in liquids with solid impurities. If a liquid contains gas impurities in the form of small bubbles, breakdown is the result of heating of the liquid in strong electric fields. In the locations with the highest current density, the liquid boils, the size of the gas bubbles increases, they merge and form gaseous channels between the electrodes, and the breakdown medium is again the gas plasma.

## Breakdown in Solids

It is known that the current in solid insulators does not obey Ohm's law in strong electric fields. The current density increases almost exponentially with the electric field, and at a certain field magnitude it jumps to very high magnitudes at which a specimen of a material is destroyed. The two known kinds of electric breakdown are thermal and electrical breakdowns. The former is the result of material heating by the electric current. Destruction of a sample of a material happens when, at a certain voltage, the amount of heat produced by the current exceeds the heat release through the sample surface; the breakdown voltage in this case is proportional to the square root of the ratio of the thermal conductivity and electrical conductivity of the material. The electrical breakdown results from the tunneling of the charge carriers from electrodes or from the valence band or from the impurity levels into the conduction band, or by the impact ionization. The tunnel effect breakdown happens mainly in thin layers, e.g., in thin p-n junctions. Otherwise, the impact ionization mechanism dominates. For this mechanism, the dielectric strength of an insulator can be estimated using Boltzmann's kinetic equation for electrons in a crystal.

In the following tables, the dielectric strength values are for room temperature and normal atmospheric pressure, unless indicated otherwise.

\* The unit of electric field in the SI system is newton per coulomb or volt per meter.

\*\* For example, the U.S. standard ASTM D149 is based on use of symmetrical electrodes, while per U.K. standard BS2918 one electrode is a plane and the other is a rod with the axis normal to the plane.

**Table 1**  
**Dielectric Strength of Gases**

<b>Material</b>	<b>Dielectric* Strength</b>	<b>Ref.</b>	<b>Material</b>	<b>Dielectric* Strength</b>	<b>Ref.</b>
Nitrogen, N <sub>2</sub>	1.00		Trichlorofluoromethane, CCl <sub>3</sub> F	3.50	1
Hydrogen, H <sub>2</sub>	0.50	1,2		4.53	2
Helium, He	0.15	1	Trichloromethane, CHCl <sub>3</sub>	4.2	1
Oxygen, O <sub>2</sub>	0.92	2		4.39	2
Air	0.97	6	Methylamine, CH <sub>3</sub> NH <sub>2</sub>	0.81	1
Air (flat electrodes), kV/mm	3.0	3	Difluoromethane, CH <sub>2</sub> F <sub>2</sub>	0.79	2
Air, kV/mm	0.4-0.7	4	Trifluoromethane, CHF <sub>3</sub>	0.71	2
Air, kV/mm	1.40	5	Bromochlorodifluoromethane, CF <sub>2</sub> ClBr	3.84	2
Neon, Ne	0.25	1	Chlorodifluoromethane, CHClF <sub>2</sub>	1.40	1
	0.16	2		1.11	2
Argon, Ar	0.18	2	Dichlorofluoromethane, CHCl <sub>2</sub> F	1.33	1
Chlorine, Cl <sub>2</sub>	1.55	1		2.61	2
Carbon monoxide, CO	1.02	1	Chlorofluoromethane, CH <sub>2</sub> ClF	1.03	1
	1.05	2	Hexafluoroethane, C <sub>2</sub> F <sub>6</sub>	1.82	1
Carbon dioxide, CO <sub>2</sub>	0.88	1		2.55	2
	0.82	2	Ethyne (Acetylene), C <sub>2</sub> H <sub>2</sub>	1.10	1
	0.84	6		1.11	2
Nitrous oxide, N <sub>2</sub> O	1.24	2	Chloropentafluoroethane, C <sub>2</sub> ClF <sub>5</sub>	2.3	1
Sulfur dioxide, SO <sub>2</sub>	2.63	2		3.0	6
	2.68	6	Dichlorotetrafluoroethane, C <sub>2</sub> Cl <sub>2</sub> F <sub>4</sub>	2.52	1
Sulfur monochloride, S <sub>2</sub> Cl <sub>2</sub>	1.02	1	Chlorotrifluoroethylene, C <sub>2</sub> ClF <sub>3</sub>	1.82	2
(at 12.5 Torr)			1,1,1-Trichloro-2,2,2-trifluoroethane	6.55	2
Thionyl fluoride, SOF <sub>2</sub>	2.50	1	1,1,2-Trichloro-1,2,2-trifluoroethane	6.05	2
Sulfur hexafluoride, SF <sub>6</sub>	2.50	1	Chloroethane, C <sub>2</sub> H <sub>5</sub> Cl	1.00	1
	2.63	2	1,1-Dichloroethane	2.66	2
Sulfur hexafluoride, SF <sub>6</sub> , kV/mm	8.50	7	Trifluoroacetonitrile, CF <sub>3</sub> CN	3.5	1
	9.8	8	Acetonitrile, CH <sub>3</sub> CN	2.11	2
Perchloryl fluoride, ClO <sub>3</sub> F	2.73	1	Dimethylamine, (CH <sub>3</sub> ) <sub>2</sub> NH	1.04	1
Tetrachloromethane, CCl <sub>4</sub>	6.33	1	Ethylamine, C <sub>2</sub> H <sub>5</sub> NH <sub>2</sub>	1.01	1
	6.21	2	Ethylene oxide (oxirane), CH <sub>3</sub> CHO	1.01	1
Tetrafluoromethane, CF <sub>4</sub>	1.01	1	Perfluoropropene, C <sub>3</sub> F <sub>6</sub>	2.55	2
Methane, CH <sub>4</sub>	1.00	1	Octafluoropropane, C <sub>3</sub> F <sub>8</sub>	2.19	1
	1.13	2		2.47	2
Bromotrifluoromethane, CF <sub>3</sub> Br	1.35	1	3,3,3-Trifluoro-1-propene, CH <sub>2</sub> CHCF <sub>3</sub>	2.11	2
	1.97	2	Pentafluoroisocycanoethane, C <sub>2</sub> F <sub>5</sub> NC	4.5	1
Bromomethane, CH <sub>3</sub> Br	0.71	2	1,1,1,4,4,4-Hexafluoro-2-butyne, CF <sub>3</sub> CCCF <sub>3</sub>	5.84	2
Chloromethane, CH <sub>3</sub> Cl	1.29	2	Octafluorocyclobutane, C <sub>4</sub> F <sub>8</sub>	3.34	2
Iodomethane, CH <sub>3</sub> I	3.02	2	1,1,1,2,3,4,4,4-Octafluoro-2-butene	2.8	1
Iodomethane, CH <sub>3</sub> I, at 370 Torr	2.20	7	Decafluorobutane, C <sub>4</sub> F <sub>10</sub>	3.08	1
Dichloromethane, CH <sub>2</sub> Cl <sub>2</sub>	1.92	2	Perfluorobutanenitrile, C <sub>3</sub> F <sub>7</sub> CN	5.5	1
Dichlorodifluoromethane, CCl <sub>2</sub> F <sub>2</sub>	2.42	1	Perfluoro-2-methyl-1,3-butadiene, C <sub>5</sub> F <sub>8</sub>	5.5	1
	2.63	2,6	Hexafluorobenzene, C <sub>6</sub> F <sub>6</sub>	2.11	2
Chlorotrifluoromethane, CClF <sub>3</sub>	1.43	1	Perfluorocyclohexane, C <sub>6</sub> F <sub>12</sub> , (saturated vapor)	6.18	2
	1.53	2			

\*Relative to nitrogen, unless units of kV/mm are indicated.

**Table 2**  
**Dielectric Strength of Liquids**

Material	Dielectric strength kV/mm	Ref.	Material	Dielectric strength kV/mm	Ref.
Helium, He, liquid, 4.2 K	10	9		20.4	15
Static	10	11		179	17,18
Dynamic	5	11	Ethylbenzene, C <sub>8</sub> H <sub>10</sub>	226	17,18
	23	12	Propylbenzene, C <sub>9</sub> H <sub>12</sub>	250	17,18
Nitrogen, N <sub>2</sub> , liquid, 77K			Isopropylbenzene, C <sub>9</sub> H <sub>12</sub>	238	17,18
Coaxial cylinder electrodes	20	10	Decane, C <sub>10</sub> H <sub>22</sub>	192	17,18
Sphere to plane electrodes	60	10	Synthetic Paraffin Mixture		
Water, H <sub>2</sub> O, distilled	65-70	13	Synfluid 2cSt PAO	29.5	37
Carbon tetrachloride, CCl <sub>4</sub>	5.5	14	Butylbenzene, C <sub>10</sub> H <sub>14</sub>	275	17,18
	16.0	15	Isobutylbenzene, C <sub>10</sub> H <sub>14</sub>	222	17,18
Hexane, C <sub>6</sub> H <sub>14</sub>	42.0	16	Silicone oils—polydimethylsiloxanes, (CH <sub>3</sub> ) <sub>3</sub> Si-O-[Si(CH <sub>3</sub> ) <sub>2</sub> ] <sub>x</sub> -O-Si(CH <sub>3</sub> ) <sub>3</sub>		
Two 2.54 cm diameter spherical electrodes, 50.8 μm space	156	17,18	Polydimethylsiloxane silicone fluid	15.4	20
Cyclohexane, C <sub>6</sub> H <sub>12</sub>	42-48	16	Dimethyl silicone	24.0	21,22
2-Methylpentane, C <sub>6</sub> H <sub>14</sub>	149	17,18	Phenylmethyl silicone	23.2	22
2,2-Dimethylbutane, C <sub>6</sub> H <sub>14</sub>	133	17,18	Silicone oil, Basilone M50	10-15	23
2,3-Dimethylbutane, C <sub>6</sub> H <sub>14</sub>	138	17,18	Mineral insulating oils	11.8	6
Benzene, C <sub>6</sub> H <sub>6</sub>	163	17,18	Polybutene oil for capacitors	13.8	6
Chlorobenzene, C <sub>6</sub> H <sub>5</sub> Cl	7.1	14	Transformer dielectric liquid	28-30	6
	18.8	15	Isopropylbiphenyl capacitor oil	23.6	6
2,2,4-Trimethylpentane, C <sub>8</sub> H <sub>18</sub>	140	17,18	Transformer oil	110.7	24
Phenylxylylethane	23.6	19	Transformer oil Agip ITE 360	9-12.6	23
Heptane, C <sub>7</sub> H <sub>16</sub>	166	17,18	Perfluorinated hydrocarbons		
2,4-Dimethylpentane, C <sub>7</sub> H <sub>16</sub>	133	17,18	Fluorinert FC 6001	8.0	23
Toluene, C <sub>6</sub> H <sub>5</sub> CH <sub>3</sub>	199	17,18	Fluorinert FC 77	10.7	23
	46	16	Perfluorinated polyethers		
	12.0	14	Galden XAD (Mol. wt. 800)	10.5	23
	20.4	15	Galden D40 (Mol. wt. 2000)	10.2	23
Octane, C <sub>8</sub> H <sub>18</sub>	16.6	14	Castor oil	65	25

**Table 3**  
**Dielectric Strength of Solids**

Material	Dielectric strength kV/mm	Ref	Material	Dielectric strength kV/mm	Ref
Sodium chloride, NaCl, crystalline	150	26	Phlogopite, amber, natural	118	6
Potassium bromide, KBr, crystalline	80	26	Fluorophlogopite, synthetic	118	6
Ceramics			Glass-bonded mica	14.0-15.7	6
Alumina (99.9% Al <sub>2</sub> O <sub>3</sub> )	13.4	6,27a	Thermoplastic Polymers		
Aluminum silicate, Al <sub>2</sub> SiO <sub>5</sub>	5.9	6	Polypropylene	23.6	6
Berillia (99% BeO)	13.8	6,27b	Amide polymer nylon 6/6, dry	23.6	6
Boron nitride, BN	37.4	6	Polyamide-imide copolymer	22.8	6
Cordierite, Mg <sub>2</sub> Al <sub>4</sub> Si <sub>5</sub> O <sub>18</sub>	7.9	6,27c	Modified polyphenylene oxide	21.7	6
Forsterite, Mg <sub>2</sub> SiO <sub>4</sub>	9.8	28	Polystyrene	19.7	6
Porcelain	35-160	26	Polymethyl methacrylate	19.7	6
Steatite, Mg <sub>3</sub> Si <sub>4</sub> O <sub>11</sub> •H <sub>2</sub> O	9.1-15.4	6	Polyetherimide	18.9	6
Titanates of Mg, Ca, Sr, Ba, and Pb	20-120	3	Amide polymer nylon 11(dry)	16.7	6
Barium titanate, glass bonded	>30	36	Polysulfone	16.7	6
Zirconia, ZrO <sub>2</sub>	11.4	29	Styrene-acrylonitrile copolymer	16.7	6
Glasses			Acrylonitrile-butadiene-styrene	16.7	6
Fused silica, SiO <sub>2</sub>	470-670	26	Polyethersulfone	15.7	6
Alkali-silicate glass	200	26	Polybutylene terephthalate	15.7	6
Standard window glass	9.8-13.8	28	Polystyrene-butadiene copolymer	15.7	6
Micas			Acetal homopolymer	15.0	6
Muscovite, ruby, natural	118	6	Acetal copolymer	15.0	6

**Table 3**  
**Dielectric Strength of Solids (continued)**

<b>Material</b>	<b>Dielectric strength kV/mm</b>	<b>Ref.</b>	<b>Material</b>	<b>Dielectric strength kV/mm</b>	<b>Ref.</b>
Polyphenylene sulfide	15.0	6	Varnishes		
Polycarbonate	15.0	6	Vacuum-pressure impregnated baking		
Acetal homopolymer resin (molding resin)	15.0	6	type solventless polyester varnish		
Acetal copolymer resin	15.0	6	Rigid, two-part	70.9	6
Thermosetting Molding Compounds			Semiflexible high-bond thixotropic	78.7	6
Glass-filled allyl	15.7	6	Rigid high-bond high-flash	68.9	6
(Type GDI-30 per MIL-M-14G)			freon-resistant		
Glass-filled epoxy, electrical grade	15.4	6	Baking type epoxy varnish		
Glass-filled phenolic	15.0	6	Solventless, rigid, low viscosity,	90.6	6
(Type GPI-100 per MIL-M-14G)			one-part		
Glass-filled alkyd/polyester	14.8	6	Solventless, semiflexible, one-part	82.7	6
(Type MAI-60 per MIL-M-14G)			Solventless, semirigid, chemical	106.3	6
Glass-filled melamine	13.4	6	resistant, low dielectric constant		
(Type MMI-30 per MIL-M-14G)			Solvable, for hermetic electric motors	181.1	6
Extrusion Compounds for High-Temperature Insulation			Polyurethane coating		
Polytetrafluoroethylene	19.7	6	Clear conformal, fast cure		
Perfluoroalkoxy polymer	21.7	6	Standard conditions	78.7	6
Fluorinated ethylene-propylene copolymer	19.7	6	Immersion conditions	47.2	6
Ethylene-tetrafluoroethylene copolymer	15.7	6	Insulating Films and Tapes		
Polyvinylidene fluoride	10.2	6	Low-density polyethylene film	300	31
Ethylene-chlorotrifluoroethylene	19.3	6	(40 $\mu$ m thick)		
copolymer			Poly- <i>p</i> -xylylene film	410-590	32
Polychlorotrifluoroethylene	19.7	6	Aromatic polymer films		
Extrusion Compounds for Low-Temperature Insulation			Kapton H (Du Pont)	389-430	33
Polyvinyl chloride			Ultem (GE Plastic and Roem AG)	437-565	33
Flexible	11.8-15.7	30	Hostaphan (Hoechst AG)	338-447	33
Rigid	13.8-19.7	30	Amorphous Stabar K2000	404-422	33
Polyethylene	18.9	28	(ICI film)		
Polyethylene, low-density	21.7	6	Stabar S100 (ICI film)	353-452	33
	300	31	Polyetherimide film (26 $\mu$ m)	486	34
Polyethylene, high-density	19.7	6	Parylene N/D (poly- <i>p</i> -xylylene/poly-		
Polypropylene/polyethylene copolymer	23.6	6	dichloro- <i>p</i> -xylylene) 25 $\mu$ m film	275	6
Embedding Compounds			Cellulose acetate film	157	6
Basic epoxy resin:	19.7	6	Cellulose triacetate film	157	6
bisphenol-A/epichlorohydrin			Polytetrafluoroethylene film	87-173	6
polycondensate			Perfluoroalkoxy film	157-197	6
Cycloaliphatic epoxy: alicyclic	19.7	6	Fluorinated ethylene-propylene	197	6
diepoxy carboxylate			copolymer film		
Polyetherketone	18.9	30	Ethylene-tetrafluoroethylene film	197	6
Polyurethanes			Ethylene-chlorotrifluoroethylene	197	6
Two-component, polyol-cured	25.4	6	copolymer film		
Two-part solventless,	24.0	6	Polychlorotrifluoroethylene film	118-153.5	6
polybutylene-based			High-voltage rubber insulating tape	28	6
Silicones			Composites		
Clear two-part heat curing electrical	21.7	6	Isophthalic polyester (vinyl toluene		
grade silicone embedding resin			monomer) filled with		
Red insulating enamel (MIL-E-22118)			Calcium carbonate, CaCO <sub>3</sub>	15.0	38
Dry	47.2	6	Gypsum, CaSO <sub>4</sub>	14.4	38
Wet	11.8	6	Alumina trihydrate	15.4	38
Enamels			Clay	14.4	38
Red enamel, fast cure			BPA fumarate polyester (vinyl toluene		
Standard conditions	78.7	6	monomer) filled with		
Immersion conditions	47.2	6	Calcium carbonate	6.1	38
Black enamel			Gypsum	5.9	38
Standard conditions	70.9	6	Alumina trihydrate	11.8	38
Immersion conditions	47.2	6	Clay	12.6	38

**Table 3**  
**Dielectric Strength of Solids (continued)**

Material	Dielectric strength kV/mm	Ref.	Material	Dielectric strength kV/mm	Ref.
Polysulfone resin—30% glass fiber	16.5-18.7	38	Butyl rubber	23.6	6
Polyamid resin (Nylon 66)— 30% carbon fiber	13.0	38	Neoprene	15.7-27.6	6
Polyimide thermoset resin, glass reinforced	12.0	39	Silicone rubber	26-36	6
Polyester resin (thermoplastic)— 40% glass fiber	20.0	38	Room-temperature vulcanized silicone rubber	9.2-10.9	35
Epoxy resin (diglycidyl ether of bisphenol A), glass reinforced	16.0	40	Ureas (from carbamide to tetraphenylurea)	11.8-15.7	28
Various Insulators			Dielectric papers		
Rubber, natural	100-215	26	Aramid paper, calendered	28.7	6
			Aramid paper, uncalendered	12.2	6
			Aramid with Mica	39.4	6

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