

Units of Power, Pressure and Force

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Chapter-1

Watt

The **watt** (symbol: **W**) is a derived unit of power in the International System of Units (SI), named after the Scottish engineer James Watt (1736–1819). The unit, defined as one joule per second, measures the rate of energy conversion.

Definition

- In terms of classical mechanics, one watt is the rate at which work is done when an object's velocity is held constant at one meter per second against constant opposing force of one newton.

$$W = \frac{J}{s} = \frac{N \cdot m}{s} = \frac{kg \cdot m^2}{s^3}$$

- In terms of electromagnetism, one watt is the rate at which work is done when one ampere (A) of current flows through an electrical potential difference of one volt (V).

$$W = V \cdot A$$

Two additional unit conversions for watt can be found using the above equation and Ohm's Law.

$$W = \frac{V^2}{\Omega} = A^2 \cdot \Omega$$

Where ohm (Ω) is the SI derived unit of electrical resistance.

Examples

A person having a mass of 100 kilograms who climbs a 3 meter high ladder in 5 seconds is doing work at a rate of about 600 watts. Mass times acceleration due to gravity times height divided by the time it takes to lift the object to the given height gives the *rate of doing work* or *power*. A laborer over the course of an 8-hour day can sustain an average output of about 75 watts; higher power levels can be achieved for short intervals and by athletes.

A medium-sized passenger automobile engine is rated at 50–100 kW (kilowatts) – while cruising it will typically yield half that amount. Larger or high performance vehicles have more powerful engines.

A typical household incandescent light bulb has a power rating of 25 to 100 watts; fluorescent lamps typically consume 5 to 30 watts to produce a similar amount of light.

A typical coal powered power station produces around 600-700 MW (megawatts).

Origin and adoption as an SI unit

The watt is named after James Watt for his contributions to the development of the steam engine. The unit was recognized by the Second Congress of the British Association for the Advancement of Science in 1882. The 11th General Conference on Weights and Measures in 1960 adopted it for the measurement of power into the International System of Units (SI).

Multiples

SI multiples for watt (W)

Submultiples			Multiples		
Value	Symbol	Name	Value	Symbol	Name
10^{-1} W	dW	deciwatt	10^1 W	daW	decaWatt
10^{-2} W	cW	centiwatt	10^2 W	hW	hectowatt
10^{-3} W	mW	milliwatt	10^3 W	kW	kilowatt
10^{-6} W	μW	microwatt	10^6 W	MW	megawatt
10^{-9} W	nW	nanowatt	10^9 W	GW	gigawatt
10^{-12} W	pW	picowatt	10^{12} W	TW	terawatt
10^{-15} W	fW	femtowatt	10^{15} W	PW	petawatt
10^{-18} W	aW	attowatt	10^{18} W	EW	exawatt
10^{-21} W	zW	zeptowatt	10^{21} W	ZW	zettawatt
10^{-24} W	yW	yoctowatt	10^{24} W	YW	yottawatt

Common multiples are in **bold** face

Femtowatt

The femtowatt is equal to one quadrillionth (10^{-15}) of a watt. Technologically important powers that are measured in femtowatts are typically found in reference(s) to radio and radar receivers. For example, FM tuner performance figures for sensitivity/quieting and signal-to-noise require that the RF energy applied to the antenna input be specified in order to be meaningful. These input levels are often stated in dBf (decibels referenced to 1 femtowatt which is equal to 0.2739 microvolt across a 75 ohm load or 0.5477 microvolt

across a 300 ohm load) so that the specification takes into account the RF input impedance of the tuner.

Picowatt

The picowatt is equal to one trillionth (10^{-12}) of a watt. Technologically important powers that are measured in picowatts are typically used in reference to radio and radar receivers, and also in the science of radio astronomy.

Nanowatt

The nanowatt is equal to one billionth (10^{-9}) of a watt. A surface area of one square meter on Earth receives one nanowatt of power from a single star of apparent magnitude +3.5. Important powers that are measured in nanowatts are also typically used in reference to radio and radar receivers.

Microwatt

The microwatt is equal to one millionth (10^{-6}) of a watt. Important powers that are measured in microwatts are typically stated in medical instrumentation systems such as the EEG and the EKG, in a wide variety of scientific and engineering instruments and also in reference to radio and radar receivers. Compact solar cells for devices such as calculators and watches are typically measured in microwatts.

Milliwatt

The milliwatt is equal to one thousandth (10^{-3}) of a watt. A typical laser pointer outputs about five milliwatts of light power, whereas a typical hearing aid for people consumes less than one milliwatt.

Kilowatt

The kilowatt is equal to one thousand (10^3) watts. This unit is typically used to express the output power of engines and the power consumption of electric motors, tools, machines, and heaters. It is also a common unit used to express the electromagnetic power output of broadcast radio and television transmitters.

One kilowatt of power is approximately equal to 1.34 horsepower. A small electric heater with one heating element can use 1.0 kilowatt. The average annual electrical energy consumption of a household in the United States is about 8,900 kilowatt-hours (cf the average UK household's approx 4,700 kilowatt-hours for example), equivalent to a steady power consumption of about 1 kW for an entire year. Also, kilowatts of light power can be measured in the output pulses of some lasers.

Megawatt

The megawatt is equal to one million (10^6) watts. Many events or machines produce or sustain the conversion of energy on this scale. For example: lightning strikes, large electric motors, large warships, such as aircraft carriers, cruisers, and submarines, engineering hardware, large Server farms or data centers and some scientific research equipment, such as supercolliders, and in the output pulses of very large lasers. A large residential or commercial building may consume several megawatts in electric power and heat.

The productive capacity of electrical generators operated by a utility company is often measured in MW. On railways, modern high-powered electric locomotives typically have a peak power output of 5 or 6 MW although some produce much more—the Eurostar, for example, consumes more than 12 MW—while heavy diesel-electric locomotives typically consume 3 to 5 MW. U.S. nuclear power plants have net summer capacities between about 500 and 1300 MW.

The earliest citing of the megawatt in the Oxford English Dictionary (OED) is a reference in the 1900 Webster's International Dictionary of English Language. The OED also states that megawatt appeared in a 28 November 1947 article in the journal *Science* (506:2).

Gigawatt

The gigawatt is equal to one billion (10^9) watts or 1 gigawatt = 1000 megawatts. This unit is sometimes used for large power plants or power grids. For example, by the end of 2010 power shortages in China's Shanxi province were expected increase to 5–6 GW and the installed capacity of wind power in Germany was 25.8 GW. The largest unit (out of four) of the Belgian Nuclear Plant Doel has a peak output of 1.04 GW.

Though obscure, the "j" sound is still an accepted pronunciation.

Terawatt

The terawatt is equal to one trillion (10^{12}) watts. The total power used by humans worldwide (about 16 TW in 2006) is commonly measured in this unit. The most powerful lasers from the mid-1960s to the mid-1990s produced power in terawatts, but only for nanosecond time frames. The average stroke of lightning peaks at 1 terawatt, but these strokes only last for 30 microseconds.

Petawatt

The petawatt is equal to one quadrillion (10^{15}) watts and can be produced by the current generation of lasers for time-scales of the order of femtoseconds (10^{-15} s). Based on the average of 1.366 kW/m² of total solar irradiance the total energy flow of sunlight striking Earth's atmosphere is estimated at 174 PW (cf. Solar Constant).

Electrical and thermal watts

In the electric power industry, *megawatt electrical* (abbreviation: MW_e or MWe) is a term that refers to electric power, while *megawatt thermal* or *thermal megawatt* (abbreviations: MW_t, MW_{th}, MWt, or MWth) refers to thermal power produced. Other SI prefixes are sometimes used, for example *gigawatt electrical* (GW_e).

For example, the Embalse nuclear power plant in Argentina uses a fission reactor to generate 2109 MW_t of heat, which creates steam to drive a turbine, which generates 648 MW_e of electricity. The difference is due to the inefficiency of steam-turbine generators and the limitations of the theoretical Carnot Cycle.

Confusion of watts, watt-hours, and watts per hour

The terms power and energy are frequently confused. Power is the rate at which energy is generated and consumed.

For example, when a light bulb with a power rating of 100W is turned on for one hour, the energy used is 100 watt-hours (W•h), 0.1 kilowatt-hour, or 360 kJ. This same amount of energy would light a 40-watt bulb for 2.5 hours, or a 50-watt bulb for 2 hours. A power station would be rated in multiples of watts, but its annual energy sales would be in multiples of watt-hours. A kilowatt-hour is the amount of energy equivalent to a steady power of 1 kilowatt running for 1 hour, or 3.6 MJ.

Terms such as *watts per hour* are often misused. Watts per hour properly refers to the *change* of power per hour. Watts per hour (W/h) might be useful to characterize the ramp-up behavior of power plants. For example, a power plant that reaches a power output of 1 MW from 0 MW in 15 minutes has a ramp-up rate of 4 MW/h. Hydroelectric power plants have a very high ramp-up rate, which makes them particularly useful in peak load and emergency situations.

Major energy production or consumption is often expressed as terawatt-hours for a given period that is often a calendar year or financial year. One terawatt-hour is equal to a sustained power of approximately 114 megawatts for a period of one year.

Chapter-2

Horsepower

Horsepower (HP) is the name of several units of measurement of power. The most common definitions equal between 735.5 and 750 watts. Horsepower was originally defined to compare the output of steam engines with the power of draft horses. The unit was widely adopted to measure the output of piston engines, turbines, electric motors, and other machinery. The definition of the unit varied between geographical regions. Most countries now use the SI unit *watt* for measurement of power. With the implementation of the EU Directive 80/181/EEC on January 1, 2010, the use of horsepower in the EU is only permitted as supplementary unit.

The definition of the horsepower also has varied between different applications:

- The *mechanical horsepower*, also known as *imperial horsepower*, of exactly 550 foot-pounds per second is approximately equivalent to 745.7 watts.
- The *metric horsepower* of 75 kgf-m per second is approximately equivalent to 735.499 watts.
- The *boiler horsepower* is used for rating steam boilers and is equivalent to 34.5 pounds of water evaporated per hour at 212 degrees Fahrenheit, or 9,809.5 watts.
- One horsepower for rating electric motors is equal to 746 watts.
- Continental European electric motors used to have dual ratings, using conversion rate 0.735 kW for 1 HP
- The *Pferdestärke* PS (German translation of horsepower) is a name for a group of similar power measurements used in Germany around the end of the 19th century, all of about one metric horsepower in size.
- The Royal Automobile Club (RAC) horsepower or British tax horsepower is an estimate based on several engine dimensions.

History of the unit

The development of the steam engine provided a reason to compare the output of horses with that of the engines that could replace them. In 1702, Thomas Savery wrote in *The Miner's Friend*: "So that an engine which will raise as much water as two horses, working together at one time in such a work, can do, and for which there must be constantly kept

ten or twelve horses for doing the same. Then I say, such an engine may be made large enough to do the work required in employing eight, ten, fifteen, or twenty horses to be constantly maintained and kept for doing such a work..." The idea was later used by James Watt to help market his improved steam engine. He had previously agreed to take royalties of one third of the savings in coal from the older Newcomen steam engines. This royalty scheme did not work with customers who did not have existing steam engines but used horses instead. Watt determined that a horse could turn a mill wheel 144 times in an hour (or 2.4 times a minute). The wheel was 12 feet in radius; therefore, the horse travelled $2.4 \times 2\pi \times 12$ feet in one minute. Watt judged that the horse could pull with a force of 180 pounds. So:

$$power = \frac{work}{time} = \frac{force \times distance}{time} = \frac{(180 \text{ lbf})(2.4 \times 2\pi \times 12 \text{ ft})}{1 \text{ min}} = 32,572 \frac{\text{ft} \cdot \text{lbf}}{\text{min}}.$$

This was rounded to an even 33,000 ft·lbf/min.

Others recount that Watt determined that a pony could lift an average 220 lbf (0.98 kN) 100 ft (30 m) per minute over a four-hour working shift. Watt then judged a horse was 50% more powerful than a pony and thus arrived at the 33,000 ft·lbf/min figure.

Engineering in History recounts that John Smeaton initially estimated that a horse could produce 22,916 foot-pounds per minute. John Desaguliers increased that to 27,500 foot-pounds per minute. "Watt found by experiment in 1782 that a 'brewery horse' was able to produce 32,400 foot-pounds per minute." James Watt and Matthew Boulton standardized that figure at 33,000 the next year.

Most observers familiar with horses and their capabilities estimate that Watt was either a bit optimistic or intended to underpromise and overdeliver; few horses can maintain that effort for long. Regardless, comparison with a horse proved to be an enduring marketing tool.

A healthy human can produce about 1.2 hp briefly and sustain about 0.1 hp indefinitely; trained athletes can manage up to about 2.5 hp briefly and 0.3 hp for a period of several hours.

Horsepower from a horse

In 1993, R. D. Stevenson and R. J. Wassersug published an article calculating the upper limit to an animal's power output. The peak power over a few seconds has been measured to be as high as 14.9 hp. However, Stevenson and Wassersug observe that for sustained activity, a work rate of about 1 hp per horse is consistent with agricultural advice from both 19th and 20th century sources.

Current definitions

The following definitions have been widely used:

Mechanical horsepower $\equiv 33,000 \text{ ft}\cdot\text{lb}_f/\text{min}$

hp(I)

$$\begin{aligned} &= 550 \text{ ft}\cdot\text{lb}_f/\text{s} \\ &= 745.699872 \text{ W} \end{aligned}$$

Metric horsepower $\equiv 75 \text{ kg}_f\cdot\text{m}/\text{s}$

hp(M)

$$\equiv 735.49875 \text{ W}$$

Electrical horsepower $\equiv 746 \text{ W}$

hp(E)

Boiler horsepower $\equiv 33,475 \text{ BTU}/\text{h}$

hp(S)

$$= 9,809.5 \text{ W}$$

Hydraulic horsepower = flow rate (US gal/min) \times pressure (psi) $\times 7/12,000$

or

$$\begin{aligned} &= \text{flow rate (US gal/min)} \times \text{pressure (psi)} / 1714 \\ &= 550 \text{ ft}\cdot\text{lb}_f/\text{s} \\ &= 745.699872 \text{ W} \end{aligned}$$

In certain situations it is necessary to distinguish between the various definitions of horsepower and thus a suffix is added: hp(I) for mechanical (or imperial) horsepower, hp(M) for metric horsepower, hp(S) for boiler (or steam) horsepower and hp(E) for electrical horsepower.

Hydraulic horsepower is equivalent to mechanical horsepower. The formula given above is for conversion to mechanical horsepower from the factors acting on a hydraulic system.

Mechanical horsepower

Assuming the third CGPM (1901, CR 70) definition of standard gravity, $g_n=9.80665 \text{ m}/\text{s}^2$, is used to define the pound-force as well as the kilogram force, and the international avoirdupois pound (1959), one mechanical horsepower is:

$$\begin{aligned} \frac{1}{\text{HP}} &\equiv 33,000 \text{ ft}\cdot\text{lb}_f/\text{min} && \text{by definition} \\ &= 550 \text{ ft}\cdot\text{lb}_f/\text{s} && \text{since } 1 \text{ min} = 60 \text{ s} \\ &= && \\ &= 550 \times 0.3048 \times 0.45359237 \text{ m}\cdot\text{kg}_f/\text{s} && \text{since } 1 \text{ ft} = 0.3048 \text{ m and} \\ &= 76.0402249068 \text{ kg}_f\cdot\text{m}/\text{s} && 1 \text{ lb} = 0.45359237 \text{ kg} \end{aligned}$$

$$\begin{aligned}
&= 76.0402249068 \times 9.80665 \text{ kg}\cdot\text{m}^2/\text{s}^3 & g = 9.80665 \text{ m/s}^2 \\
&= 745.69987158227022 \text{ W} & \text{since } 1 \text{ W} \equiv 1 \text{ J/s} = 1 \text{ N}\cdot\text{m/s} = \\
& & 1 \text{ (kg}\cdot\text{m/s}^2)\cdot(\text{m/s})
\end{aligned}$$

Or given that 1 hp = 550 ft·lb_f/s, 1 ft = 0.3048 m, 1 lb_f ≈ 4.448 N, 1 J = 1 N·m, 1 W = 1 J/s: 1 hp = 746 W

Metric horsepower

Metric horsepower began in Germany in the 19th century and became popular across Europe and Asia. The various units used to indicate this definition (*PS*, *CV*, *hk*, *pk*, *ks* and *ch*) all translate to *horse power* in English, so it is common to see these values referred to as *horsepower* or *hp* in the press releases or media coverage of the German, French, Italian, and Japanese automobile companies. British manufacturers often intermix metric horsepower and mechanical horsepower depending on the origin of the engine in question. Sometimes the metric horsepower rating of an engine is conservative enough so that the same figure can be used for both 80/1269/EEC with metric hp and SAE J1349 with imperial hp.

Metric horsepower, as a rule, is defined as 0.73549875 kW, or roughly 98.6% of mechanical horsepower. This was a minor issue in the days when measurement systems varied widely and engines produced less power, but has become a major sticking point today. Exotic cars from Europe like the McLaren F1 and Bugatti Veyron are often quoted using the wrong definition, and their power output is sometimes even converted twice because of confusion over whether the original *horsepower* number was metric or mechanical.

PS

This unit (German: *Pferdestärke* = horse strength) is no longer a statutory unit, but is still commonly used in Europe, South America, Japan and India especially by the automotive and motorcycle industry. It was adopted throughout continental Europe with designations equivalent to the English *horsepower*, but mathematically different from the British unit.

DIN 66036 defines one horsepower to lift a mass of 75 kilograms within one second against the earth gravitation over a distance of one metre. Similar definitions were already common to the time of James Watt.

The PS was adopted by the Deutsches Institut für Normung (DIN) and then by the automotive industry throughout most of Europe, under varying names. In 1992, the PS was rendered obsolete by EEC directives, when it was replaced by the kilowatt as the official power measuring unit. It is still in use for commercial and advertising purposes, in addition to the kW rating, as many customers are still not familiar with the use of kilowatts for engines.

pk, ch, hk, hv, LE, k/ks, KS, KM, CP, PS

The Dutch *paardenkracht* (pk), the French *chevaux* (ch), the Swedish *hästkraft* (hk), the Finnish *hevosvoima* (hv), the Norwegian and Danish *hestekraft* (hk), the Hungarian *lóerő* (LE), the Czech *koňská síla* and Slovak *koňská sila* (k or ks), the Croatian and Serbian *konjska snaga* (KS), the Macedonian *Којнска сила* (KC), the Polish *koń mechaniczny* and Slovenian *konjska moč* (KM) and the Romanian *cal-putere* (CP) all equal the German *Pferdestärke* (PS), and are approximately equal to 735.5 W.

CV and cv

In Italian (*Cavalli*), Spanish (*Caballos de vapor*), and Portuguese (*Cavalo-vapor*), *CV* is the equivalent to the German, *PS*. It is also used as the French term for the *Pferdestärke*, but in French, this should be written in lowercase letters as *cv*.

In addition, the capital form *CV* is used in Italy and France as a unit for tax horsepower, short for, respectively, *cavalli vapore* and *chevaux vapeur* (*steam horses*). *CV* is a non-linear rating of a motor vehicle for tax purposes. The *CV* rating, or fiscal power, is $\left(\frac{P}{40}\right)^{1.6} + \frac{U}{45}$, where P is the maximum power in kilowatts and U is the amount of CO₂ emitted in grams per kilometre. The term for CO₂ measurements has only been included in the definition since 1998, so older ratings in *CV* are not directly comparable. The fiscal power has found its way into naming of automobile models, such as the popular Citroën deux-chevaux. The cheval-vapeur (ch) unit should not be confused with the French cheval fiscal (*CV*).

In the 19th century, the French had their own unit, which they used instead of the *CV* or horsepower. It was called the *poncelet* and was abbreviated *p*.

Boiler horsepower

A boiler horsepower is used for boilers in various industrial applications; however, it is considered an antiquated term and is not used in modern power plants except in North America, where it persists in industrial boiler engineering. One boiler horse power unit or BHP is equal to a boiler thermal output of 33,475 BTU/h (9.8095 kW), which is the energy rate needed to evaporate 34.5 lb (15.65 kg) of water at 212 °F (100 °C) in one hour.

The term was originally developed at the Philadelphia Centennial Exhibition in 1876, where the best steam engines of that period were tested. The average steam consumption of those engines (per output horsepower) was determined to be the evaporation of 30 lb/h of water, based on feedwater at 100 °F (38 °C), and saturated steam generated at 70 psi (480 kPa) gauge pressure. This original definition is equivalent to a boiler heat output of 33,485 BTU/h. In 1884, the ASME redefined the boiler horsepower as the thermal output equal to the evaporation of 34.5 lb/h of water "from and at" 212 °F. This considerably simplified boiler testing, and provided more accurate comparisons of the boilers at that

time. This revised definition is equivalent to a boiler heat output of 33,469 BTU/hr. Present industrial practice is to define *boiler horsepower* as a boiler thermal output equal to 33,475 BTU/h, which is very close to the original and revised definitions.

The amount of power that can be obtained by a steam engine or steam turbine based on *boiler horsepower* varies so widely that use of the term is entirely obsolete for these purposes. The term makes no distinction as to the steam pressure or temperature which is produced (both of which significantly influence engine/turbine output); it merely defines a thermal output of a boiler. Smaller steam engines often require several *boiler horsepower* to make one horsepower, and modern steam turbines can make power with as little as about 0.15 hp (boiler) thermal output per actual horsepower developed.

Electrical horsepower

The horsepower used for electrical machines is defined as exactly 746 W. The nameplates on electrical motors show their power output, not their power input

Relationship with torque

For a given torque and speed, the power may be calculated; the relationship between torque in foot-pounds, rotational speed in rpm and horsepower is:

$$P/\text{hp} = \frac{\tau/(\text{ft}\cdot\text{lbf}) \times f/(\text{rpm})}{5252}$$

Where P is power, τ is torque, and f is rotations per minute. The constant 5252 comes from $(33,000 \text{ ft}\cdot\text{lbf}/\text{min})/(2\pi \text{ rad}/\text{rev})$.

The standard equation relating torque in inch pounds, rotational speed in rpm and horsepower is:

$$P/\text{hp} = \frac{\tau/(\text{in}\cdot\text{lbf}) \times f/(\text{rpm})}{63,025}$$

Where P is power, τ is torque, and f is rotations per minute. The constant 63,025 comes from $(33,000 \text{ ft}\cdot\text{lbf}/\text{min}) \times (12 \text{ in}/\text{ft})/(2\pi \text{ rad}/\text{rev})$.

Drawbar horsepower

Drawbar horsepower (dbhp) is the power a railway locomotive has available to haul a train or an agricultural tractor to pull an implement. This is a measured figure rather than a calculated one. A special railway car called a dynamometer car coupled behind the locomotive keeps a continuous record of the drawbar pull exerted, and the speed. From these, the power generated can be calculated. To determine the maximum power

available, a controllable load is required; it is normally a second locomotive with its brakes applied, in addition to a static load.

If the drawbar force (F) is measured in pounds-force (lbf) and speed (v) is measured in miles per hour (mph), then the drawbar power (P) in horsepower (hp) is:

$$P/\text{hp} = \frac{(F/\text{lbf})(v/\text{mph})}{375}$$

Example: How much power is needed to pull a drawbar load of 2,025 pounds-force at 5 miles per hour?

$$P/\text{hp} = \frac{2025 \times 5}{375} = 27$$

The constant 375 is because 1 hp = 375 lbf·mph. If other units are used, the constant is different. When using a coherent system of units, such as SI (watts, newtons, and metres per second), no constant is needed, and the formula becomes $P = Fv$.

RAC horsepower (taxable horsepower)

This measure was instituted by the Royal Automobile Club in Britain and was used to denote the power of early 20th century British cars. Many cars took their names from this figure (hence the Austin Seven and Riley Nine), while others had names such as "40/50 hp", which indicated the RAC figure followed by the true measured power.

Taxable horsepower does not reflect developed horsepower; rather, it is a calculated figure based on the engine's bore size, number of cylinders, and a (now archaic) presumption of engine efficiency. As new engines were designed with ever-increasing efficiency, it was no longer a useful measure, but was kept in use by UK regulations which used the rating for tax purposes.

$$RACH.p. = D^2 * n / 2.5$$

where

D is the diameter (or bore) of the cylinder in inches

n is the number of cylinders

This is equal to the displacement in cubic inches divided by 10π then divided again by the stroke in inches.

Since taxable horsepower was computed based on bore and number of cylinders, not based on actual displacement, it gave rise to engines with 'undersquare' dimensions (i.e., relatively narrow bore), but long stroke; this tended to impose an artificially low limit on rotational speed (rpm), hampering the potential power output and efficiency of the engine.

The situation persisted for several generations of four- and six-cylinder British engines: for example, Jaguar's 3.4-litre XK engine of the 1950s had six cylinders with a bore of 83 mm (3.27 in) and a stroke of 106 mm (4.17 in), where most American automakers had long since moved to oversquare (wide bore, short stroke) V-8s (see, for example, the early Chrysler Hemi).

Measurement

The power of an engine may be measured or estimated at several points in the transmission of the power from its generation to its application. A number of names are used for the power developed at various stages in this process, but none is a clear indicator of either the measurement system or definition used.

In the case of an engine dynamometer, power is measured at the engine's flywheel (i.e., at the crankshaft output). With a chassis dynamometer or *rolling road*, power output is measured at the driving wheels. This accounts for the significant power loss through the drive train.

In general:

Nominal is derived from the size of the engine and the piston speed and is only accurate at a pressure of 48 kPa (7 psi).

Indicated or gross horsepower (theoretical capability of the engine) [PLAN/ 33000] minus frictional losses within the engine (bearing drag, rod and crankshaft windage losses, oil film drag, etc.), equals

Brake / net / crankshaft horsepower (power delivered directly to and measured at the engine's crankshaft)

minus frictional losses in the transmission (bearings, gears, oil drag, windage, etc.), equals

Shaft horsepower (power delivered to and measured at the output shaft of the transmission, when present in the system)

minus frictional losses in the universal joint/s, differential, wheel bearings, tire and chain, (if present), equals

Effective, True (thp) or commonly referred to as wheel horsepower (whp)

All the above assumes that no power inflation factors have been applied to any of the readings.

Engine designers use expressions other than horsepower to denote objective targets or performance, such as brake mean effective pressure (BMEP). This is a coefficient of theoretical brake horsepower and cylinder pressures during combustion.

Nominal horsepower

Nominal horsepower (nhp) is an early Nineteenth Century rule of thumb used to estimate the power of steam engines.

$n_{hp} = 7 \times \text{area of piston} \times \text{equivalent piston speed} / 33,000$

For paddle ships the piston speed was estimated as $129.7 \times (\text{stroke})^{1/3.35}$

For the nominal horsepower to equal the actual power it would be necessary for the mean steam pressure in the cylinder during the stroke to be 48 kPa (7 psi) and for the piston speed to be of the order of 54–75 m/min.

Indicated horsepower

Indicated horsepower (ihp) is the theoretical power of a reciprocating engine if it is completely frictionless in converting the expanding gas energy (piston pressure \times displacement) in the cylinders. It is calculated from the pressures developed in the cylinders, measured by a device called an *engine indicator* – hence indicated horsepower. As the piston advances throughout its stroke, the pressure against the piston generally decreases, and the indicator device usually generates a graph of pressure vs stroke within the working cylinder. From this graph the amount of work performed during the piston stroke may be calculated. It was the figure normally used for steam engines in the 19th century but is misleading because the actual power output may only be 70% to 90% of the indicated horsepower.

Brake horsepower

Brake horsepower (bhp) is the measure of an engine's horsepower before the loss in power caused by the gearbox, alternator, differential, water pump, and other auxiliary components such as power steering pump, muffled exhaust system, etc. *Brake* refers to a device which was used to load an engine and hold it at a desired RPM. During testing, the output torque and rotational speed were measured to determine the *brake horsepower*. Horsepower was originally measured and calculated by use of the indicator (a James Watt invention of the late 18th century), and later by means of a De Prony brake connected to the engine's output shaft. More recently, an engine dynamometer is used instead of a De Prony brake. The output delivered to the driving wheels is less than that obtainable at the engine's crankshaft.

British horsepower

The abbreviation *bhp* may also be used for *British horsepower* (though the usual use is Brake Horse Power), which has the same definition as the American SAE gross brake horsepower: 33,000 lb·ft/min. More information on American SAE horsepower measurements is below.

Shaft horsepower

Shaft horsepower (shp) is the power delivered to the propeller shafts of a steamship (or one powered by diesel engines or nuclear power), or an aircraft powered by a piston engine or a gas turbine engine. This shaft horsepower can be measured with instruments,

or estimated from the indicated horsepower and a standard figure for the losses in the transmission (typical figures are around 10%). This measure is uncommonly used in the automobile industry, because there, drive train losses can become significant.

Engine power test codes

Engine power test codes determine how the power and torque of an automobile engine is measured and corrected. Correction factors are used to adjust power and torque measurements to standard atmospheric conditions to provide a more accurate comparison between engines as they are affected by the pressure, humidity, and temperature of ambient air. There exist several standards for this purpose, some described below.

Society of Automotive Engineers

SAE gross power

Prior to the 1972 model year, American automakers rated and advertised their engines in brake horsepower (bhp), frequently referred to as SAE gross horsepower, because it was measured in accord with the protocols defined in SAE standards J245 and J1995. As with other brake horsepower test protocols, SAE gross hp was measured using a stock test engine, generally running with few belt-driven accessories and sometimes fitted with long tube (test headers) in lieu of the OEM exhaust manifolds. The atmospheric correction standards for barometric pressure, humidity and temperature for testing were relatively idealistic.

SAE net power

In the United States, the term *bhp* fell into disuse in 1971-72, as automakers began to quote power in terms of SAE net horsepower in accord with SAE standard J1349. Like SAE gross and other brake horsepower protocols, SAE Net hp is measured at the engine's crankshaft, and so does not account for transmission losses. However, the SAE net power testing protocol calls for standard production-type belt-driven accessories, air cleaner, emission controls, exhaust system, and other power-consuming accessories. This produces ratings in closer alignment with the power produced by the engine as it is actually configured and sold.

SAE certified power

In 2005, the SAE introduced "SAE Certified Power" with SAE J2723. This test is voluntary and is in itself not a separate engine test code but a certification of either J1349 or J1995 after which the manufacturer is allowed to advertise "Certified to SAE J1349" or "Certified to SAE J1995" depending on which test standard have been followed. To attain certification the test must follow the SAE standard in question, take place in a ISO9000/9002 certified facility and be witnessed by an SAE approved third party.

A few manufacturers such as Honda and Toyota switched to the new ratings immediately, with multi-directional results; the rated output of Cadillac's supercharged Northstar V8 jumped from 440 to 469 hp (330 to 350 kW) under the new tests, while the rating for Toyota's Camry 3.0 L *IMZ-FE* V6 fell from 210 to 190 hp (160 to 140 kW). The ES330 and Camry SE V6 were previously rated at 225 hp but the ES330 dropped to 218 hp (163 kW) while the Camry declined to 210 hp (160 kW). The first engine certified under the new program was the 7.0 L LS7 used in the 2006 Chevrolet Corvette Z06. Certified power rose slightly from 500 to 505 hp (370 to 377 kW).

While Toyota and Honda are retesting their entire vehicle lineups, other automakers generally are retesting only those with updated powertrains. For example, the 2006 Ford Five Hundred is rated at 203 horsepower, the same as that of 2005 model. However, the 2006 rating does not reflect the new SAE testing procedure as Ford is not going to spend the extra expense of retesting its existing engines. Over time, most automakers are expected to comply with the new guidelines.

SAE tightened its horsepower rules after some engineers noticed parts of the old test could be subjected to different interpretations. Under the old testing procedures, there were small factors that required a judgment call: how much oil was in the crankcase, how the engine controls were calibrated and whether a vehicle was tested with premium fuel. In some cases, such can add up to a change in horsepower ratings. A road test editor at Edmunds.com, John Di Pietro, said decreases in horsepower ratings for some '06 models are not that dramatic. For vehicles like a midsize family sedan, it is likely that the reputation of the manufacturer will be more important.

Deutsches Institut für Normung 70020

DIN 70020 is a standard from German DIN regarding road vehicles. Because the German word for *horsepower* is *Pferdestärke*, in Germany it is commonly abbreviated to *PS*. DIN hp is measured at the engine's output shaft, and is usually expressed in metric (Pferdestärke) rather than mechanical horsepower.

Economic Commission for Europe R24

ECE R24 is a European standard for the approval of compression ignition engine emissions, installation and measurement of engine power. It is similar to DIN 70020 standard, but with different requirements for connecting an engine's fan during testing causing it to absorb less power from the engine.

80/1269/EEC

80/1269/EEC of 16 December 1980 is a European Union standard for road vehicle engine power.

International Organization for Standardization

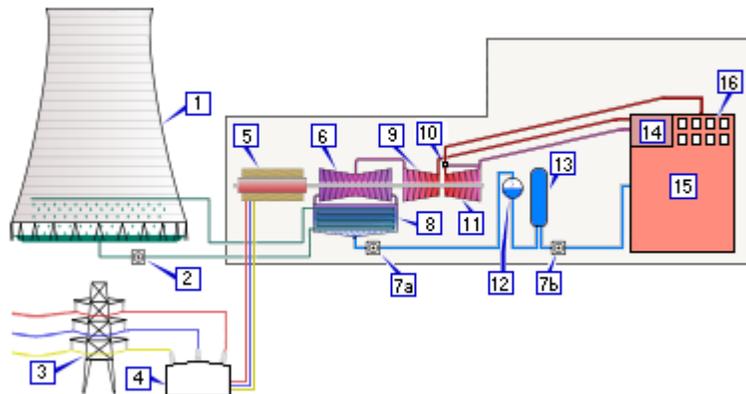
- ISO 14396 specifies the additional and method requirement for determining the power of reciprocating internal combustion engines when presented for an ISO 8178 exhaust emission test. It applies to reciprocating internal combustion engines for land, rail and marine use excluding engines of motor vehicles primarily designed for road use.
- ISO 1585 is an engine net power test code intended for road vehicles.
- ISO 2534 is an engine gross power test code intended for road vehicles
- ISO 4164 is an engine net power test code intended for mopeds.
- ISO 4106 is an engine net power test code intended for motorcycles.
- ISO 9249 is an engine net power test code intended for earth moving machines.

Japanese Industrial Standard D 1001

JIS D 1001 is a Japanese net, and gross, engine power test code for automobiles or trucks having a spark ignition, diesel engine, or fuel injection engine.

Chapter-3

Orders of Magnitude



A thermal power plant generates electric power from thermal energy

This page lists examples of the power in watts produced by various different sources of energy. They are grouped by orders of magnitude, and each section covers three **orders of magnitude**, or a factor of one thousand.

Below 1 Watt

zeptowatt (10^{-21} watt)

- ~ 10 zW – *tech*: approximate power of Galileo space probe's radio signal (when at Jupiter) as received on earth by a 70-meter DSN antenna.

attowatt (10^{-18} watt)

- 1 aW – *phys*: approximate power scale at which operation of nanoelectromechanical systems are overwhelmed by thermal fluctuations.

- 100 aW The GPS signal strength measured at the surface of the Earth is about – 160dBw (1 x 10⁻¹⁶ watts), which is roughly equivalent to viewing a 25-watt light bulb from a distance of 10,000 miles.

femtowatt (10⁻¹⁵ watt)

- 2.5 fW – *tech*: minimum discernible signal at the antenna terminal of a good FM radio receiver
- 10 fW (–110 dBm) – *tech*: approximate lower limit of power reception on digital spread-spectrum cell phones

picowatt (10⁻¹² watt)

- 1 pW – *biomed*: average power consumption of a human cell
- 18.4 pW – *tech*: (1.84 x 10⁻¹¹ watt) power lost by a proton in the Large Hadron Collider at 7000 GeV
- 150 pW – *biomed*: power entering a human eye from a 100-watt lamp 1 km away

nanowatt (10⁻⁹ watt)

- 2–15 nW – *tech*: power consumption of 8-bit PIC microcontroller chips when in "sleep" mode

microwatt (10⁻⁶ watt)

- 1 μW – *tech*: approximate consumption of a quartz wristwatch
- 3 μW – *astro*: cosmic microwave background radiation per square meter

milliwatt (10⁻³ watt)

- 5 mW – *tech*: laser in a CD-ROM drive
- 5-10 mW – *tech*: laser in a DVD player
- 70 mW - *tech*: antennae power in a typical consumer wireless router

Between 1 and 1000 Watts

watt

- 4 W – *tech*: the power consumption of an incandescent night light
- 5 W – *legal*: maximum power output of a CB or hand-held radio transceiver
- 14 W – *tech*: the power consumption of a typical household compact fluorescent light bulb
- 20–40 W – *biomed*: approximate power consumption of the human brain
- 30–40 W – *tech*: the power consumption of a typical household fluorescent tube light

- 60 W – *tech*: the power consumption of a typical household incandescent light bulb
- 100 W – *biomed*: approximate basal metabolic rate used by an adult human body
- 120 W – *tech*: power output of 1 m² solar panel in full sunlight (approx. 12% efficiency)[at sea level]
- 130 W – *tech*: peak power consumption of a Pentium 4 CPU
- 253 W (2,215 kWh/year) – *geo*: per capita average power use of the world in 2001
- 290 W – *units*: approximately 1000 BTU/hour
- 300–400 W – *tech*: PC GPU Nvidia Geforce Fermi 480 power consumption
- 400 W – *tech*: legal limit of power output of an amateur radio station in the United Kingdom
- 500 W – *biomed*: power output (useful work plus heat) of a person working hard physically
- 745.7 W – *units*: 1 horsepower
- 750 W – *astro*: approximately the amount of sunshine falling on a square metre of the Earth's surface on a clear day in March for northern temperate latitudes
- 909 W – *biomed*: peak output power of a healthy human (nonathlete) during a 30-second cycle sprint at 30.1 degree Celsius.

Above 1000 Watts

kilowatt (10³ watts)

- 1.1 kW - *tech*: power of a microwave oven
- 1.366 kW – *astro*: power received from the sun at the earth's orbit per square metre
- 1.5 kW – *tech*: legal limit of power output of an amateur radio station in the United States
- up to 2 kW – *biomed*: approximate short-time power output of sprinting professional cyclists
- 1 kW to 3 kW – *tech*: heat output of a domestic electric kettle.
- 3.6 kW – *tech*: Synchrotron radiation power lost per ring in the Large Hadron Collider at 7000 GeV
- 3.3-6.6 kW – *eco*: average photosynthetic power output per square kilometer of ocean
- 30 kW – power generated by the four motors of GEN H-4 one-man helicopter
- 11.4 kW – average power consumption per person in the United States as of 2009
- 16-32 kW – *eco*: average photosynthetic power output per square kilometer of land
- 10 kW to 50 kW – *tech*: nominal power of clear channel AM
- 50 kW to 100 kW – *tech*: highest allowed ERP for an FM band radio station in the United States.
- 40 kW to 200 kW – *tech*: approximate range of power output of typical automobiles
- 167 kW – *tech*: power consumption of UNIVAC 1 computer

- 250 kW to 800 kW – *tech*: approximate range of power output of 'supercars'

megawatt (10^6 watts)

- 1.3 MW – *tech*: power output of P-51 Mustang fighter aircraft
- 1.5 MW – *tech*: peak power output of GE's standard wind turbine
- 2.5 MW – *biomed*: peak power output of a blue whale
- 3 MW – *tech*: mechanical power output of a diesel locomotive
- 10 MW – *tech*: highest ERP allowed for an UHF television station
- 10.3 MW – *geo*: electrical power output of Togo
- 16 MW – *tech*: rate at which a typical gasoline pump transfers chemical energy to a vehicle
- 17 to 80 MW – *tech*: approximate maximum power output of a Nd:YAG laser used in Particle Image Velocimetry (100mJ over 6ns to 400mJ over 5ns, both at 532 nm)
- 75 MW – *tech*: maximum power output of one GE90 jet engine as installed on the Boeing 777
- 140 MW – *tech*: average power consumption of a Boeing 747 passenger aircraft
- 190 MW – *tech*: peak power output of a Nimitz-class aircraft carrier
- 900 MW – *tech*: electric power output of a CANDU nuclear reactor
- 959 MW – *geo*: average electrical power consumption of Zimbabwe in 1998

The productive capacity of electrical generators operated by utility companies is often measured in MW. Few things can sustain the transfer or consumption of energy on this scale; some of these events or entities include: lightning strikes, naval craft (such as aircraft carriers and submarines), engineering hardware, and some scientific research equipment (such as supercolliders and large lasers).

For reference, about 10,000 100-watt lightbulbs or 5,000 computer systems would be needed to draw 1 megawatt. Also, 1 MW equals approximately 1360 horsepower. Modern high-powered diesel-electric railroad locomotives typically have a peak power output of 3–5 MW, whereas a typical modern nuclear power plant produces on the order of 500–2000 MW peak output.

gigawatt (10^9 watts)

- 1.3 GW – *tech*: electric power output of Manitoba Hydro Limestone hydroelectric generating station
- 2.074 GW – *tech*: peak power generation of Hoover Dam
- 2.1 GW – *tech*: peak power generation of Aswan Dam
- 4.116 GW – *tech*: installed capacity of Kendal Power Station, the world's largest coal-fired power plant.
- 8.21 GW – *tech*: capacity of the Kashiwazaki-Kariwa Nuclear Power Plant, the world's largest nuclear power plant.
- 12.6 GW – *tech*: electrical power generation of the Itaipu Dam
- 12.7 GW – *geo*: average electrical power consumption of Norway in 1998

- 18.3 GW – *tech*: current electrical power generation of the Three Gorges Dam the world's largest hydroelectric power plant of any type.
- 55 GW – *tech* peak daily electrical power consumption of Great Britain in November 2008.
- 74 GW – *tech*: total installed wind turbine capacity at end of 2006.
- 190 GW – *tech*: average power consumption of the first stage of the Saturn V rocket

terawatt (10¹² watts)

- 2 TW – *astro*: approximate power generated between the surfaces of Jupiter and its moon Io due to Jupiter's tremendous magnetic field.
- 3.34 TW – *geo*: average total (gas, electricity, etc.) power consumption of the U.S. in 2005
- 15 TW – *geo*: average total power consumption of the human world in 2004
- 44 TW – *geo*: average total heat flux from earth's interior
- 75 TW – *eco*: global net primary production (= biomass production) via photosynthesis
- 50 to 200 TW – *weather*: rate of heat energy release by a hurricane
- 290 TW – *tech*: the power the Z machine reaches in 1 billionth of a second when it is fired
- 300 TW – *tech*: power reached by the extremely high-power Hercules laser from the University of Michigan.

petawatt (10¹⁵ watts)

- 1.1 PW – *tech*: world's most powerful laser pulses by laser still in operation (claimed on 31 March 2008 by Texas Center for High Intensity Laser Science at The University of Texas at Austin).
- 1.25 PW – *tech*: world's most powerful laser pulses (claimed on 23 May 1996 by Lawrence Livermore Laboratory).
- 1.4 PW – *geo*: estimated heat flux transported by the Gulf Stream.
- 4 PW – *geo*: estimated total heat flux transported by earth's atmosphere and oceans away from the equator towards the poles.
- 10–100 PW *geo*: estimated total power output of a Type-I civilization on the Kardashev scale.
- 174.0 PW – *astro*: total power received by the earth from the sun

zettawatt (10²¹ watts)

- 135 ZW – *astro*: approximate luminosity of Wolf 359
- 250 ZW - *tech*: z-machine electric discharge

yottawatt (10^{24} watts)

- 5.3 YW – *tech*: power produced by the Tsar Bomba fusion bomb, the most powerful man made device
- 384.6 YW – *astro*: luminosity of the sun
- 400 YW – *geo*: estimated total power output of a Type-II civilization on the Kardashev scale.

greater than one thousand yottawatts

- 3.31×10^{31} W – *astro*: approximate luminosity of Beta Centauri
- 1.23×10^{32} W – *astro*: approximate luminosity of Deneb
- 5×10^{36} W – *astro*: approximate luminosity of the Milky Way galaxy.
- 4×10^{37} W – *astro*: estimated total power output of a Type-III civilization on the Kardashev scale.
- 1×10^{40} W – *astro*: approximate luminosity of a quasar
- 1×10^{42} W – *astro*: approximate luminosity of the Local Supercluster
- 1×10^{45} W – *astro*: approximate luminosity of a gamma-ray burst
- 2×10^{49} W – *astro*: approximate total luminosity of all the stars in the observable universe
- 3.63×10^{52} W – *phys*: The Planck power, the basic unit of power in the Planck units.

Chapter-4

Diverse Units of Power

Airwatt

An **airwatt** or **air watt** is a unit of power very close to the watt which is used for various vacuum cleaning systems, such as vacuum cleaners. The airwatt is derived from English units. ASTM International defines the airwatt as $0.117354 * F * S$, where F is the rate of air flow in ft^3/m and S is the pressure in inches of water. This makes one airwatt equal to 0.9983 watts.

The airwatt is useful measurement of vacuum power, since the power carried by a fluid flow (in the case of a typical house vacuum the fluid is air) is equal to pressure times volumetric flow rate. This could be a more useful figure than the electrical power drawn by the vacuum system's motor, since the efficiency of motor and vacuum systems varies.

Formula

$$\begin{aligned}\text{cleaning power (air watts)} &= \text{airflow (CFM)} \times \text{suction (inches of water)} / 8.5 \\ &= \text{airflow (m}^3/\text{s)} \times \text{suction (Pa)}\end{aligned}$$

Mercury (Hg) is heavier than water so, 1" of Hg= 13.5" of water. In other words, 10" Hg is the same vacuum level as 135" of H₂O lift. The CFM figure can't be evaluated alone, any more than the lift figure can. The following shows why:

Lift vs. Airflow: These two factors are interdependent. They are tied to one another; if one goes up, the other goes down. This is called an inverse relationship.

Let's suppose that when you look at the vacuum gauge of your truck mount the reading is a level of 6" Hg. Looking at chart 1, we see that at this level of lift, the system is capable of moving about 175 CFM.

Now suppose you do something to the system such as add more hose or improve the wand seal. Now your gauge reads a level of 10" Hg. From the chart, you can see that you now hit the performance curve at point "B" and that the airflow has dropped to about 150 CFM. So, as one factor (lift) went up, another (airflow) came down. They have an inverse relationship. Fact: The most effective cleaning is accomplished when there is proper balance between lift and airflow.

Air watts measured at the vacuum's motor can differ by as much as 50% (depending on the type of vacuum) from the air watts measured at the end of the hose. This is most noted in central vacuums.

Nominal watt

Nominal wattage is used to simplify the measurement of the efficiency of a loudspeaker.

The impedance of a loudspeaker varies with frequency. This means that if different sine wave tones are fed into the loudspeaker at the same voltage (or the same current), the amount of electric power consumed will vary.

By convention, loudspeakers are designed to generate the same sound pressure level (SPL) at the listener for the same voltage at varying frequencies - regardless of the variation in electric power. This permits a loudspeaker to be used with an amplifier having a low internal impedance and a flat frequency response is realized for the combined amplifier/loudspeaker system.

However, an amplifier with a low internal impedance delivers more electrical output power when the load impedance reduces (until the impedances become approximately matched). Such high power levels could cause damage to either the amplifier or the amplifier's power supply, or the circuit connected to the amplifier's output (including the loudspeaker).

Therefore, an additional convention exists whereby loudspeaker manufacturers specify a conservative estimate of the average impedance that the loudspeaker will present while playing typical music. This is called the *nominal impedance*. Amplifiers can therefore be safely specified to operate into a load that has this *nominal impedance* (or higher, but not lower).

Typical nominal impedances for speakers include 4, 6, 8 and 16 Ω (ohms), with 4 Ω being most common in in-car loudspeakers, and 8 Ω being most common elsewhere. A loudspeaker with an 8 Ω nominal impedance may exhibit actual impedances ranging from approximately 5 to 100 Ω depending on frequency.

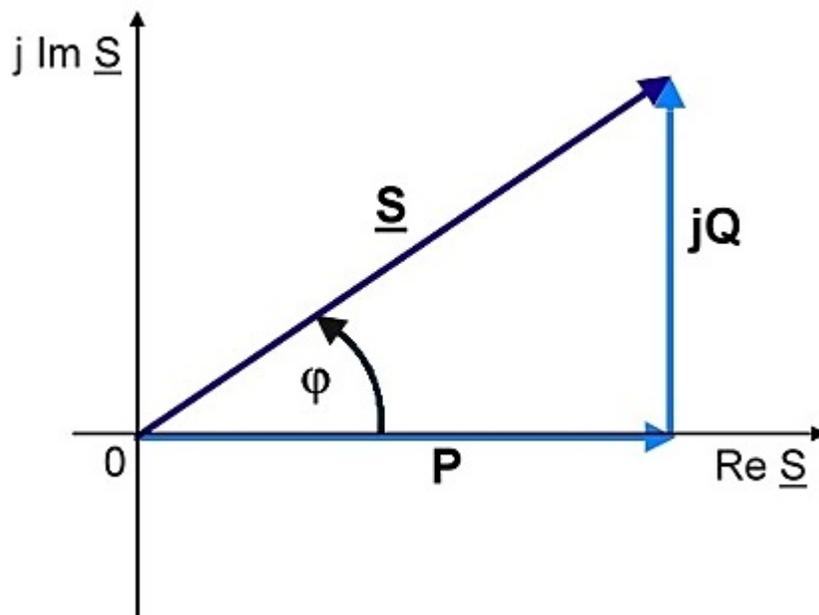
In this context, the nominal wattage is the *theoretical* electric power that *would* be transferred from amplifier to speaker *if* the loudspeaker was actually exhibiting its

nominal impedance. The actual electric power may vary from about twice the nominal power down to less than one tenth.

Loudspeaker efficiency is measured with respect to nominal power in order to emulate the situation outlined above where a low internal impedance amplifier is used with a loudspeaker. The convention is to supply one nominal watt during testing. If the nominal impedance is 4 ohms, the voltage would be 2 volts. If the nominal impedance is 8Ω , the voltage would be 2.83 volts.

Volt-ampere

A **volt-ampere** (VA) is the unit used for the apparent power in an electrical circuit, equal to the product of root-mean-square (RMS) voltage and RMS current. In direct current (DC) circuits, this product is equal to the real power (active power) in watts. Volt-amperes are useful only in the context of alternating current (AC) circuits (sinusoidal voltages and currents of the same frequency).



Apparent power is the vector sum of real (P) and reactive (jQ) AC power vectors

While both the volt-ampere (abbreviated VA) and the watt have the dimension of power (time rate of energy), they do not have the same meaning. Some devices, including Uninterruptible Power Supplies (UPSs), have ratings both for maximum VAs and maximum watts.

The VA rating is limited by the maximum permissible current, and the watt rating by the power-handling capacity of the device. When a UPS powers equipment which presents a reactive load with a low power factor (e.g., a computer), neither limit may safely be exceeded.

Volt-ampere reactive

In alternating current power transmission and distribution, **volt-ampere reactive (var)** is a unit used to measure reactive power in an AC electric power system. Reactive power exists in an ac circuit when the current and voltage are not changing at the same time. The correct symbol is var and not VAr or VAR, but the latter two terms are widely used. The term *var* was proposed by the Romanian electrical engineer Constantin Budeanu and introduced in 1930 by the IEC in Stockholm, which has adopted it as the unit for reactive power.

Vars may be considered as either the imaginary part of apparent power, or the power flowing into a reactive load, where voltage and current are specified in volts and amperes. The two definitions are equivalent.

Reactive power

A sinusoidally alternating voltage applied to a purely resistive load results in an alternating current that is fully in phase with the voltage. In many applications it is however common for there to be a reactive component to the system, that is, the system possesses capacitance, inductance, or both. These electrical properties cause the current to change phase with respect to the voltage: capacitance tending the current to lead the voltage in phase, and inductance to lag it.

For sinusoid currents and voltages at the same frequency, reactive power in vars is the product of the RMS voltage and current, or the apparent power, multiplied by the sine of the phase angle between the voltage and the current. The reactive power Q , (measured in units of volt-amperes reactive or var), is given by:

$$Q = V_{\text{rms}} I_{\text{rms}} \sin(\phi)$$

where ϕ is the phase angle between the voltage and current.

Only effective power, the actual power delivered to or consumed by the load, is expressed in watts. Imaginary power is properly expressed in volt-amperes reactive.

Watt-peak

Watt-peak (Wp) is a measure of the nominal power of a photovoltaic solar energy device under laboratory illumination conditions. Related units such as **kilowatt-peak** or **kilowatts-peak (kWp)** and **megawatts-peak** are also used, and in the context of domestic installations kWp is the most common unit encountered.

Measurement of Nominal Power

The nominal power of a photovoltaic module is determined by measuring current and voltage while varying resistance under defined illumination. The conditions are specified in standards such as IEC 61215, IEC 61646 and UL 1703; specifically the light intensity is $1000\text{W}/\text{m}^2$, with a spectrum similar to sunlight hitting the earth's surface at latitude 35°N in the summer (airmass 1.5) and temperature of the cells at 25°C . The power is measured while varying the resistive load on the module between open and closed circuit. The maximum power measured is the nominal power of the module in "**W_p**". The nominal power divided by the light power that falls on the module ($\text{area} \times 1000\text{W}/\text{m}^2$) is the **efficiency**. Watts peak is a convenient measure because it enables one to compare one module with another and track industry capacities and shipments. Equivalent measures can be used for wind electricity generators, though obviously the specification of ideal conditions is different.

Power output in real conditions

The output of photovoltaic systems varies with the intensity of sunshine and other conditions. The more sun, the more power the PV module will generate. Losses will occur due to non-ideal alignment of the module in tilt and/or orientation, high temperature, module power mismatch, soiling and DC to AC conversion. Importantly the maximum power a module can generate can easily exceed the nominal power, anywhere where the intensity of sunlight exceeds $1000\text{W}/\text{m}^2$ (which corresponds roughly to midday in summer in, for example, Germany)

Cost-per-watt

Although watt-peak is a convenient measure, and is the standardized number in the photovoltaic industry on which prices, sales and growth numbers are based, it is arguably not the most important number for cost-effectiveness. Since a solar panel's job is to generate electric power, the amount of power that it generates under average conditions should be the most important number to evaluate. It can happen that a panel from brand A and a panel of brand B give exactly the same watt-peak in a laboratory test, but their power output is different in a real installation. This difference can be caused by the fact that the relation of performance to temperature or insulation is different for the two cells. For example, a low efficiency cell will become hotter, and with higher temperature

the efficiency will go down, reducing useful energy conversion further. The ratio of a power source's average to peak production is its capacity factor.

Solar luminosity

The **solar luminosity**, L_{\odot} , is a unit of luminosity or radiant power (power emitted in the form of photons) conventionally used by astronomers to give the luminosities of stars. One solar luminosity is equal to the current accepted luminosity of the Sun, which is 3.839×10^{26} W, or 3.839×10^{33} erg/s. The value is slightly higher, 3.939×10^{26} W (equivalent to 4.382×10^9 kg/s or $2.107 \times 10^{-15} M_{\odot}/d$) if the solar neutrino radiation is included as well as electromagnetic radiation. The Sun is a weakly variable star and its luminosity therefore fluctuates. The major fluctuation is the eleven-year solar cycle (sunspot cycle), which causes a periodic variation of about $\pm 0.1\%$. Any other variation over the last 200–300 years is thought to be much smaller than this.

Determination

The solar luminosity is related to the solar irradiance measured at the Earth or by satellites in Earth orbit. The mean irradiance at the top of the Earth's atmosphere is sometimes known as the solar constant, I_{\odot} . Irradiance is defined as power per unit area, so the solar luminosity (total power emitted by the Sun) is the irradiance received at the Earth (solar constant) multiplied by the area of the sphere whose radius is the mean distance between the Earth and the Sun:

$$L_{\odot} = 4\pi k I_{\odot} A^2$$

where A is the unit distance (the value of the astronomical unit in metres) and k is a constant (whose value is very close to one) that reflects the fact that the mean distance from the Earth to the Sun is not exactly one astronomical unit.

Chapter-5

Torr

The **torr** (symbol: **Torr**) is a non-SI unit of pressure with the ratio of 760 to 1 standard atmosphere, chosen to be roughly equal to the fluid pressure exerted by a millimeter of mercury, *i.e.* a pressure of 1 Torr is *approximately* equal to 1 mmHg. Note that the symbol is spelled exactly the same as the unit, but the symbol is capitalized, as is customary in metric units derived from names. It was named after Evangelista Torricelli, an Italian physicist and mathematician who discovered the principle of the barometer in 1644.

History

Torricelli attracted considerable attention when he demonstrated the first mercury barometer to the general public. He is credited with giving the first modern explanation of atmospheric pressure. Scientists at the time were familiar with small fluctuations in height that occurred in barometers. When these fluctuations were explained as a manifestation of changes in atmospheric pressure, the science of meteorology was born.

Over time, 760 millimeters of mercury (abbreviated mmHg) came to be regarded as the standard atmospheric pressure. In honor of Torricelli, the torr was defined as a unit of pressure equal to one mmHg.

In 1954, the definition of the *atmosphere* was revised by the *10e Conférence Générale des Poids et Mesures (10th CGPM)* to the currently accepted definition: one atmosphere is equal to 101,325 pascals. The torr was then re-defined as $\frac{1}{760}$ of one atmosphere. This was necessary in place of the definition of a torr as 1 mmHg, because the height of mercury changes at different temperatures and gravities.

SI units of pressure

The SI unit of pressure is the *pascal* (symbol: Pa), defined as one newton per square meter. Other units of pressure are defined in terms of SI units. These include:

- The bar (symbol: bar), defined as 100 kPa exactly.

- The atmosphere (symbol: atm), defined as 101.325 kPa exactly.
- The torr (symbol: Torr), defined as $\frac{1}{760}$ atm exactly.

These four pressure units are used in different settings. For example, the bar is used in meteorology to report atmospheric pressures. The torr, a more convenient unit for low pressures, is used in high-vacuum physics and engineering.

Pressure units						
	Pascal (Pa)	Bar (bar)	Technical atmosphere (at)	Atmosphere (atm)	Torr (Torr)	Pound- force per square inch (psi)
1 Pa	$\equiv 1 \text{ N/m}^2$	10^{-5}	1.0197×10^{-5}	9.8692×10^{-6}	7.5006×10^{-3}	145.04×10^{-6}
1 bar	100,000	$\equiv 10^6 \text{ dyn/cm}^2$	1.0197	0.98692	750.06	14.5037744
1 at	98,066.5	0.980665	$\equiv 1 \text{ kgf/cm}^2$	0.96784	735.56	14.223
1 atm	101,325	1.01325	1.0332	$\equiv 1 \text{ atm}$	760	14.696
1 torr	133.322	1.3332×10^{-3}	1.3595×10^{-3}	1.3158×10^{-3}	$\equiv 1 \text{ Torr};$ $\approx 1 \text{ mmHg}$	19.337×10^{-3}
1 psi	6.894×10^3	68.948×10^{-3}	70.307×10^{-3}	68.046×10^{-3}	51.715	$\equiv 1 \text{ lbf/in}^2$

Example reading: $1 \text{ Pa} = 1 \text{ N/m}^2 = 10^{-5} \text{ bar} = 10.197 \times 10^{-6} \text{ at} = 9.8692 \times 10^{-6} \text{ atm} = 7.5006 \times 10^{-3} \text{ torr} = 145.04 \times 10^{-6} \text{ psi}$
etc.

Manometric units of pressure

Manometric units are units such as *millimeters of mercury* or *centimeters of water* that depend on an assumed density of a fluid and an assumed acceleration of gravity. The use of these units is discouraged. Nevertheless, manometric units are used routinely in medicine and physiology, and they continue to be used in areas as diverse as weather reporting and scuba diving.

The *millimeter of mercury* (symbol: *mmHg*) is defined as the pressure exerted at the base of a column of fluid exactly 1 mm high, when the density of the fluid is exactly 13.5951 g/cm^3 , at a place where the acceleration of gravity is exactly 9.80665 m/s^2 . Under most conditions, 1 mmHg is approximately equal to 1 Torr.

There are several things to notice about this definition:

- A fluid density of 13.5951 g/cm^3 was chosen for this definition because this is the approximate density of mercury at 0°C . The definition, therefore, assumes a particular value for the density of mercury. The density can depend on temperature, exogenous pressure, and other similar variables, so those have to assume certain conventional, normal values as well.

- The definition assumes a particular value for the acceleration of gravity: the standard gravity $g_0 = 9.80665 \text{ m/s}^2$. In theory, the precise acceleration would vary, and the measurement would have to be recalibrated against the local value; in weightless conditions, this kind of measurement would not even make sense.
- The definition does not address the quality of the vacuum, including the vapor pressure of the mercury, above the column of fluid.

In practice, of course, measurements are made using local values, which vary little enough at the Earth's surface. These assumptions limit both the validity and the precision of the mmHg as a unit of pressure.

According to the UK's National Physical Laboratory (NPL):

The need to assume fixed and exact – but ultimately incorrect – values of liquid density and acceleration due to gravity will inherently limit knowledge of the relationship between [the millimeter of mercury] and the pascal.

By contrast, the magnitude of pressure values expressed in the SI pressure unit, the pascal, can flex (albeit not by much) to take account of technological improvements in the underlying definitions of mass, length and time – the SI base quantities from which pressure is derived.

The performance of modern transducers approaches the precision required to distinguish between the torr and the millimeter of mercury.

The NPL concludes

Thus, in the near future, the accuracy claims being made for otherwise state-of-the-art instruments scaled in manometric units will become inherently inferior.

Even now, confusion and large errors abound through the use of differing definitions, including alternative values of 'standard' gravity and varying assumptions about the density and temperature of the fluid.

Misunderstandings about temperature assumptions alone can lead to errors of several tenths of a percent and there are many stories of this leading to major mistakes in pressure measurement.

Manometric units in medicine and physiology

In medicine, the millimetre of mercury (measured with a sphygmomanometer) is the "gold standard" for blood pressure measurement.

In physiology, manometric units are used to measure Starling forces. Other applications include:

- Intraocular pressure (tonometry)
- Cerebrospinal fluid pressure
- Intracranial pressure
- Intramuscular pressure (compartment syndrome)
- Central venous pressure
- Pulmonary artery catheterization
- Mechanical ventilation

Manometric results in medicine are sometimes given in torr.

This is usually incorrect, since the torr and the millimetre of mercury are not the same thing.

Pressures obtained with a manometer (or its transducer equivalent) should be reported in millimetres of mercury.

Conversion factors

The mmHg is defined as $(13.5951 \times 9.80665) \text{ Pa} = 133.322387415 \text{ Pa}$, which is approximated with known accuracies of density of mercury and gravitational acceleration. The torr is defined as 1/760 of one atmosphere, while the atmosphere is defined as 101.325 kPa. Therefore, one torr is equal to $101325 / 760 \text{ Pa}$. The decimal form of this fraction (133.322368421...) is, unfortunately for practical use, an infinitely long, periodically repeating decimal, as is its reciprocal.

The relationship between the torr and the mmHg is:

- 1 Torr = 0.999999857533699... mmHg
- 1 mmHg = 1.000000142466321... Torr

The difference between one mmHg and one torr, as well as between one atmosphere (101.325 kPa) and 760 mmHg (101.3250144354 kPa), is less than one part in seven million (or less than 0.000015%). This small difference is negligible for most applications outside metrology.

The unit mmHg as used in medicine is in general given relative to the atmospheric pressure. This means that when a doctor tells you you have a blood pressure of 100 mmHg, this is 100mmHg above atmospheric. So on a day when the barometric pressure is 760 your absolute pressure is actually $760 + 100 = 860 \text{ mmHg} = 860/760 \times 10^5 \text{ Pa}$.

Chapter-6

Pascal and Pounds Per Square Inch

Pascal

Pascal



A pressure gauge reading in psi (red scale) and kPa (black scale)

Unit information

Unit system:	SI derived unit
Unit of...	Pressure / Stress
Symbol:	Pa
Named after:	Blaise Pascal
In SI base units:	$1 \text{ Pa} = 1 \text{ kg}/(\text{m}\cdot\text{s}^2)$

The **pascal** (symbol: **Pa**) is the SI derived unit of pressure, internal pressure, stress, Young's modulus and tensile strength, named after the French mathematician, physicist, inventor, writer and Catholic philosopher Blaise Pascal. It is a measure of force per unit area, defined as one newton per square metre. In everyday life, the pascal is perhaps best

known from meteorological barometric pressure reports, where it occurs in the form of hectopascals (1 hPa \equiv 100 Pa) or kilopascals (1 kPa \equiv 1000 Pa). In other contexts, the kilopascal is commonly used, for example on bicycle tire labels. One hectopascal corresponds to about 0.1% and one kilopascal to about 1% of atmospheric pressure (near sea level). One hectopascal is equivalent to one millibar; one standard atmosphere is exactly equal to 1013.25 hPa or 101325 Pa. The equivalent Imperial unit is pounds per square inch.

hPa = hectopascal where 1 hPa = 100 Pa

kPa = kilopascal where 1 kPa = 1000 Pa

MPa = megapascal where 1MPa = 1000000 Pa

Definition

The pascal can be expressed using SI derived units, or alternatively solely SI base units, as:

$$1 \text{ Pa} = 1 \frac{\text{N}}{\text{m}^2} = 1 \frac{\text{kg}}{\text{m} \cdot \text{s}^2}$$

Where N is the newton, m is the metre, kg is the kilogram, and s is the second.

Pressure units						
	Pascal (Pa)	Bar (bar)	Technical atmosphere (at)	Atmosphere (atm)	Torr (Torr)	Pound- force per square inch (psi)
1 Pa	$\equiv 1 \text{ N/m}^2$	10^{-5}	1.0197×10^{-5}	9.8692×10^{-6}	7.5006×10^{-3}	145.04×10^{-6}
1 bar	100,000	$\equiv 10^6 \text{ dyn/cm}^2$	1.0197	0.98692	750.06	14.5037744
1 at	98,066.5	0.980665	$\equiv 1 \text{ kgf/cm}^2$	0.96784	735.56	14.223
1 atm	101,325	1.01325	1.0332	$\equiv 1 \text{ atm}$	760	14.696
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1 psi	6.894×10^3	68.948×10^{-3}	70.307×10^{-3}	68.046×10^{-3}	51.715	$\equiv 1 \text{ lbf/in}^2$

Example reading: $1 \text{ Pa} = 1 \text{ N/m}^2 = 10^{-5} \text{ bar} = 10.197 \times 10^{-6} \text{ at} = 9.8692 \times 10^{-6} \text{ atm} = 7.5006 \times 10^{-3} \text{ torr} = 145.04 \times 10^{-6} \text{ psi}$
etc.

Origin

The unit is named after Blaise Pascal, the eminent French mathematician, physicist, and philosopher noted for his experiments with a barometer, an instrument to measure air pressure. The name *pascal* was adopted for the SI unit newton per square metre by the 14th CGPM in 1971.

This SI unit is named after Blaise Pascal. As with every SI unit whose name is derived from the proper name of a person, the first letter of its symbol is upper case (**Pa**). When an SI unit is spelled out in English, it should always begin with a lower case letter (**pascal**), except where *any* word would be capitalized, such as at the beginning of a sentence or in capitalized material such as a title. Note that "degree Celsius" conforms to this rule because the "d" is lowercase.

—Based on *The International System of Units*, section 5.2.

Miscellaneous

Standard atmospheric pressure is $101,325 \text{ Pa} = 101.325 \text{ kPa} = 1013.25 \text{ hPa} = 1013.25 \text{ mbar} = 760 \text{ Torr}$. This definition is used for pneumatic fluid power (ISO R554), and in the aerospace (ISO 2533) and petroleum (ISO 5024) industries.

In 1985, IUPAC recommended that standard atmospheric pressure should be harmonized to $100,000 \text{ Pa} = 1 \text{ bar} = 750 \text{ Torr}$. The same definition is used in the compressor and the pneumatic tool industries (ISO 2787).

The Unicode computer character set has dedicated symbols Pa (U+33A9) for Pa and kPa (U+33AA) for kPa, but these exist merely for backward-compatibility with some older ideographic character-sets and are therefore deprecated.

Uses

The pascal (Pa) or kilopascal (kPa) as a unit of pressure measurement is widely used throughout the world and largely replaces the pounds per square inch (psi) unit, except in some countries still using the Imperial measurement system.

Tectonophysicists use the gigapascal (GPa) in measuring or calculating tectonic forces within the earth.

In Solid Mechanics, megapascals ($\text{MPa} = \text{N/mm}^2$) or gigapascals ($\text{GPa} = \text{kN/mm}^2$) are commonly used to measure stiffness of materials.

Another unit for pressure measurement in common use today is millimetres of water (1 mm H₂O = 9.80665 Pa).

Meteorologists worldwide have for a long time measured atmospheric pressure in millibars. After the introduction of SI units, many preferred to preserve the customary pressure figures. Therefore, meteorologists use hectopascals (hPa) today for air pressure, which are equivalent to millibars, while similar pressures are given in kilopascals in practically all other fields, where the hecto prefix is hardly ever used. Since official metrication, meteorologists in Canada use kilopascals (kPa), see for example CTV News, weather; current conditions in Montreal and Environment Canada weather, current conditions in Montreal, although in some other countries hectopascals are still in use, see for example KNMI, KMI, DWD, JMA, MDD and NOAA.

1 hectopascal (hPa) \equiv 100 Pa \equiv 1 mbar.

1 kilopascal (kPa) \equiv 1000 Pa \equiv 10 hPa \equiv 10 mbar.

In the cgs system, the unit of pressure is the barye (symbol **ba**), which is equal to one decipascal. The older kg(force)/cm² corresponds to 98.0665 kPa, but is often rounded to 100 kPa in practice.

In the former mts system, the unit of pressure is the pièze (symbol **pz**), which is equal to one kilopascal.

Vehicle owners' guides now specify tire inflation in kilopascals.

Airtightness testing of buildings is measured at 50 Pa or 0.2 inches of water.

Pounds per square inch



A pressure gauge reading in psi (red scale) and kPa (black scale)

The **pound per square inch** or, more accurately, **pound-force per square inch** (symbol: **psi** or **lbf/in²** or **lb_f/in²** or **lbf/sq in** or **lb_f/sq in**) is a unit of pressure or of stress based on avoirdupois units. It is the pressure resulting from a force of one pound-force applied to an area of one square inch:

1 psi approximately equals 6,894.757 Pa, where pascal (Pa) is the SI unit of pressure.

Relation to other measures

Other abbreviations are used that append a modifier to "psi". However, the US National Institute of Standards and Technology recommends that, to avoid confusion, any modifiers be instead applied to the quantity being measured rather than the unit of measure. For example, " $P_g = 100$ psi" rather than " $P = 100$ psig".

- psia (pounds-force per square inch absolute) — gauge pressure plus local atmospheric pressure. Replace " x psia" with " $P_a = x$ psi".
- psid (psi difference) — difference between two pressures. Replace " x psid" with " $\Delta P = x$ psi".
- psig (pounds-force per square inch gauge) - pressure relative to the surrounding atmosphere. Replace " x psig" with " $P_g = x$ psi".
- psivg (psi vented gauge) — difference between the measuring point and the local pressure. Replace " x psivg" with " $P_{vg} = x$ psi".
- psisg (psi sealed gauge) — difference between a chamber of air sealed at atmospheric pressure and the pressure at the measuring point. Replace " x psisg" with " $P_{sg} = x$ psi".

Psig v. Psia

Psig (pound-force per square inch gauge) is a unit of pressure relative to the surrounding atmosphere. By contrast, *psia* (pound-force per square inch absolute) measures pressure relative to a vacuum (such as that in space).

At sea level, Earth's atmosphere actually exerts a pressure of 14.696 psi. Humans do not feel this pressure because the internal pressure of their bodies matches the external pressure. If a pressure gauge is calibrated to read zero in a vacuum, then at sea level on Earth it would read 14.7 psi. Thus, a reading of 30 psig on Earth represents an absolute pressure of 44.7 psi. More generally, x psia = $(x + 14.696)$ psig.

Psi is often used instead of psig, possibly causing confusion.

ksi

The ksi ("kilo-pound[-force] per square inch") is 1000 psi, combining the prefix kilo with the psi abbreviation. It is occasionally used in materials science, civil and mechanical engineering to specify stress and Young's modulus.

Magnitude

- Blood Pressure Average human blood pressure (120/80): 2.32044psi/1.54696psi
- Boost Pressure Provided By an Automotive Turbocharger(common): $P_g = 6 - 15$ psi
- Atmospheric pressure at sea level (standard): $P_a = 14.7$ psi
- Automobile tire overpressure (common): $P_g = 32$ psi

- Bicycle tire overpressure (common): $P_g = 65$ psi
- Workshop or garage air tools: $P_g = 90$ psi
- Air brake (rail) or Air brake (road vehicle) reservoir overpressure (common): $90 \text{ psi} \leq P_g \leq 120 \text{ psi}$
- Road racing bicycle tire overpressure: $P_g = 120$ psi
- Steam locomotive fire tube boiler (UK, 20th century): $150 \text{ psi} \leq P_g \leq 225 \text{ psi}$
- Union Pacific Big Boy steam locomotive boiler: 300 psi
- Natural gas pipelines: 800 to 1000 psi
- Full SCBA Self Contained Breathing Apparatus for toxic atmospheres: 2216 psi
- Full scuba tank overpressure (common): $P_g = 3000$ psi
- Commercial jet airliner hydraulic pressure: 3000 psi
- Airbus A380 hydraulic system: 5000 psi
- Water jet cutter: 40,000 psi - 100,000 psi

Conversions

	Pressure units					
	Pascal (Pa)	Bar (bar)	Technical atmosphere (at)	Atmosphere (atm)	Torr (Torr)	Pound- force per square inch (psi)
1 Pa	$\equiv 1 \text{ N/m}^2$	10^{-5}	1.0197×10^{-5}	9.8692×10^{-6}	7.5006×10^{-3}	145.04×10^{-6}
1 bar	100,000	$\equiv 10^6 \text{ dyn/cm}^2$	1.0197	0.98692	750.06	14.5037744
1 at	98,066.5	0.980665	$\equiv 1 \text{ kgf/cm}^2$	0.96784	735.56	14.223
1 atm	101,325	1.01325	1.0332	$\equiv 1 \text{ atm}$	760	14.696
1 torr	133.322	1.3332×10^{-3}	1.3595×10^{-3}	1.3158×10^{-3}	$\equiv 1 \text{ Torr};$ $\approx 1 \text{ mmHg}$	19.337×10^{-3}
1 psi	6.894×10^3	68.948×10^{-3}	70.307×10^{-3}	68.046×10^{-3}	51.715	$\equiv 1 \text{ lbf/in}^2$

Example reading: $1 \text{ Pa} = 1 \text{ N/m}^2 = 10^{-5} \text{ bar} = 10.197 \times 10^{-6} \text{ at} = 9.8692 \times 10^{-6} \text{ atm} = 7.5006 \times 10^{-3} \text{ torr} = 145.04 \times 10^{-6} \text{ psi}$
etc.

Chapter-7

Atmosphere (unit) and Bar (unit)

Atmosphere (unit)

The **standard atmosphere** (symbol: **atm**) is an international reference pressure defined as 101,325 Pa and formerly used as unit of pressure. For practical purposes it has been replaced by the bar which is 100,000 Pa. The difference of about 1% is not significant for many applications, and is within the error range of common pressure gauges.

History

In 1954 the 10th Conférence Générale des Poids et Mesures (CGPM) adopted *standard atmosphere* for general use and affirmed its definition of being precisely equal to 1,013,250 dynes per square centimeter (101 325 Pa). This value was intended to represent the mean atmospheric pressure at mean sea level at the latitude of Paris, France, and as a practical matter, truly reflects the mean sea level pressure for many of the industrialized nations (those with latitudes similar to Paris).

In chemistry, the original definition of “Standard Temperature and Pressure” (STP) was a reference temperature of 0 °C (273.15 K) and pressure of 101.325 kPa (1 atm). However, in 1982, the International Union of Pure and Applied Chemistry (IUPAC) recommended that for the purposes of specifying the physical properties of substances, “*the standard pressure*” should be defined as precisely 100 kPa (exactly 1 bar).

Pressure units and equivalencies

	Pressure units					Pound-force per square inch (psi)
	Pascal (Pa)	Bar (bar)	Technical atmosphere (at)	Atmosphere (atm)	Torr (Torr)	
1 Pa	$\equiv 1 \text{ N/m}^2$	10^{-5}	1.0197×10^{-5}	9.8692×10^{-6}	7.5006×10^{-3}	145.04×10^{-6}
1 bar	100,000	$\equiv 10^6 \text{ dyn/cm}^2$	1.0197	0.98692	750.06	14.5037744
1 at	98,066.5	0.980665	$\equiv 1 \text{ kgf/cm}^2$	0.96784	735.56	14.223
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1 torr	133.322	1.3332×10^{-3}	1.3595×10^{-3}	1.3158×10^{-3}	$\equiv 1 \text{ Torr}; \approx 1 \text{ mmHg}$	19.337×10^{-3}
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etc.

A pressure of 1 atm can also be stated as:

- $\equiv 1.013 \ 25 \text{ bar}$
- $\equiv 1013.25 \text{ hectopascal (hPa)}$
- $\equiv 1013.25 \text{ millibars (mbar, also mb)}$
- $\equiv 760 \text{ torr}^{[B]}$
- $\approx 760.001 \text{ mm-Hg, } 0 \text{ }^\circ\text{C, subject to revision as more precise measurements of mercury's density become available}^{[B, C]}$
- $\approx 29.9213 \text{ in-Hg, } 0 \text{ }^\circ\text{C, subject to revision as more precise measurements of mercury's density become available}^{[C]}$
- $\approx 1.033 \ 227 \ 452 \ 799 \ 886 \text{ kgf/cm}^2$
- $\approx 1.033 \ 227 \ 452 \ 799 \ 886 \text{ technical atmosphere}$
- $\approx 1033.227 \ 452 \ 799 \ 886 \text{ cm-H}_2\text{O, } 4 \text{ }^\circ\text{C}^{[A]}$
- $\approx 406.782 \ 461 \ 732 \ 2385 \text{ in-H}_2\text{O, } 4 \text{ }^\circ\text{C}^{[A]}$
- $\approx 14.695 \ 948 \ 775 \ 5134 \text{ pounds-force per square inch (psi)}$
- $\approx 2116.216 \ 623 \ 673 \ 94 \text{ pounds-force per square foot (psf)}$

Notes:

^A This is the customarily-accepted value for cm-H₂O, 4 °C. It is precisely the product of 1 kg-force per square centimeter (one technical atmosphere) times 1.013 25 (bar/atmosphere) divided by 0.980 665 (one gram-force). It is not accepted practice to define the value for water column based on a true physical realization of water (which would be 99.997 495% of this value because the true maximum density of Vienna

Standard Mean Ocean Water is 0.999 974 95 kg/l at 3.984 °C). Also, this “physical realization” would *still* ignore the 8.285 cm–H₂O reduction that would actually occur in a true physical realization due to the vapor pressure over water at 3.984 °C.

^B Torr and mm-Hg, 0°C are often taken to be identical. For most practical purposes (to 5 significant digits), they are interchangeable.

^C NIST value of 13.595 078(5) g/ml assumed for the density of Hg at 0 °C

Other applications

Scuba divers and others use the word *atmosphere* and "atm" in relation to pressures that are relative to mean atmospheric pressure at sea level (1.013 bar). For example, a partial pressure of oxygen is calibrated typically using air at sea level, so is expressed in units of atm.

The old European unit technical atmosphere (at) is roughly equal to the gauge pressure under 10 m of water; 1 at = 98066.5 Pa.

Bar (unit)

The **bar** is a unit of pressure equal to 100 kilopascals, and roughly equal to the atmospheric pressure on Earth at sea level. Other units derived from the bar are the **megabar** (symbol: **Mbar**), **kilobar** (symbol: **kbar**), **decibar** (symbol: **dbar**), **centibar** (symbol: **cbar**), and **millibar** (symbol: **mbar** or **mb**). They are not SI units, nor are they cgs units, but they are accepted for use with the SI. The bar is widely used in descriptions of pressure because it is only about 1% smaller than the atmosphere, and is legally recognized in countries of the European Union.

Except for the power of ten, the definition of bar fits in the sequence of SI pressure units (Pa, kPa, MPa), namely, 1 bar \equiv 100,000 Pa = 100 kPa = 0.1 MPa. This is in contrast to the well-known unit of pressure, atmosphere, which now is *defined* to be 1.01325 bar exactly.

The bar and the millibar were introduced by the British meteorologist William Napier Shaw in 1909. William Napier Shaw was the director of the Meteorological Office in London from 1907 to 1920.

Barg is a unit of gauge pressure, i.e. pressure in bars above ambient or atmospheric pressure.

Definition

- 1 atm (atmosphere) = 1.01325 bar
- 1 kbar = 1000 bar = 100,000 kPa = 1,000,000,000 dyn/cm² = 100 MPa = 0.1 GPa

- 1 bar = 100 kPa = 1,000,000 dynes per square centimeter (baryes) = 0.987 atm (atmospheres) = 14.5038 psi = 29.53 inHg = 750.06 torr
- 1 dbar = 0.1 bar = 10 kPa = 100,000 dyn/cm²
- 1 cbar = 0.01 bar = 1 kPa
- 1 mbar = 0.001 bar = 0.1 kPa = 1 hPa (hectopascal) = 1,000 dyn/cm²

Example conversion: 1 atm pressure = 1.01325 bar = 1.01325 x 10⁵ Pa = 1.01325 x 10⁵ N/m²

Origin

The word *bar* has its origin in the Greek word *βάρος* (baros), meaning weight. Its official symbol is "bar"; the earlier "b" is now deprecated, but still often seen especially in "mb" rather than the proper "mbar" for millibars.

The bar and millibar were introduced by Sir Napier Shaw in 1909 and internationally adopted in 1929.

Usage

Atmospheric air pressure is often given in millibars where "standard" sea level pressure (1 atm) is defined as 1013.25 mbar (hPa), equal to 1.01325 bar. Despite millibars not being an SI unit, meteorologists and weather reporters worldwide have long measured air pressure in millibars. After the advent of SI units, some meteorologists began using hectopascals (symbol hPa) which are numerically equivalent to millibars. For example, the weather office of Environment Canada uses kilopascals and hectopascals on their weather maps. In contrast, Americans are familiar with the use of the millibar in US reports of hurricanes and other cyclonic storms.

In water, there is an approximate numerical equivalence between the change in pressure in decibars and the change in depth from the sea surface in metres. Specifically, an increase of 1 decibar occurs for every 1.019716 metre increase in depth close to the surface. As a result, decibars are commonly used in oceanography.

Many engineers worldwide use the bar as a unit of pressure because, in much of their work, using pascals would involve using very large numbers.

In the automotive field, turbocharger boost is often described in the United Kingdom in terms of the bar.

Unicode has a character for "mb": mb, U+33D4, but it exists only for compatibility with legacy Asian encodings. There is also a character "bar": bar, U+3374.

The kilobar is commonly used in geological systems, particularly in experimental Petrology.

Absolute pressure and gauge pressure

Bourdon tube pressure gauges, vehicle tire gauges, and many other types of pressure gauges are zero referenced to atmospheric pressure, which means that they measure the pressure above atmospheric pressure (which is around 1 bar); this is *gauge* pressure and is often referred to as *barg* (spoken "bar gauge"). In contrast, absolute pressures are zero referenced to a complete vacuum and when expressed in bar are often referred to as *bara*. Thus, the absolute pressure of any system is the gauge pressure of the system plus atmospheric pressure. The usage of *bara* and *barg* is now deprecated, with qualification of the physical property being preferred, e.g., "The gauge pressure is 2.3 bar; the absolute pressure is 3.3 bar".

In the United States, where pressures are still often expressed in pounds per square inch (symbol *psi*), gauge pressures are referred to as *psig* and absolute pressures are referred to as *psia*. Gauge pressure is also sometimes spelled as *gage pressure*.

Sometimes, the context in which the word pressure is used helps to identify it as meaning either the absolute or gauge pressure. However, in truth, whenever a pressure is expressed in any units (bar, Pa, psi, atm, etc.), it should be denoted in some manner as being either absolute or gauge pressure to avoid any possible misunderstanding. One recommended way of doing so is to spell out what is meant, for example as *bar gauge* or *kPa absolute*.

Chapter-8

Diverse Units of Pressure

Centimetre of water

A **centimetre of water** (US spelling **centimeter of water**, abbreviated **cmH₂O**) is a less commonly used unit of pressure derived from pressure head calculations using metrology. It is frequently used to measure the central venous pressure, the intracranial pressure while sampling cerebrospinal fluid, as well as determining pressures during mechanical ventilation or in water supply networks (then usually in metres water column). It is also a common unit of pressure in the speech sciences.

It is defined as the pressure exerted by a column of water of 1 cm in height at 4 °C (temperature of maximum density) at the standard acceleration of gravity.

This unit is commonly used to specify the pressure to which a CPAP machine is set after a polysomnogram.

$$\begin{aligned} 1 \text{ cmH}_2\text{O} &= 98.0638 \text{ pascals} \\ &\approx 0.98064 \text{ mbar or hectopascals} \\ &\approx 0.39370 \text{ inH}_2\text{O} \\ &\approx 0.00096781 \text{ atm} \\ &\approx 0.73554 \text{ torr} \\ &\approx 0.73554 \text{ mmHg} \\ &\approx 0.028958 \text{ inHg} \\ &\approx 0.014223 \text{ psi} \end{aligned}$$

Inch of mercury

Inches of mercury, (inHg) is a unit of measurement for pressure. It is still widely used for barometric pressure in weather reports and aviation in the United States, but is seldom used elsewhere.

It is defined as the pressure exerted by a column of mercury of 1 inch in height at 32 °F (0 °C) at the standard acceleration of gravity.

$$1 \text{ inHg} = 3,386.389 \text{ pascals at } 0 \text{ } ^\circ\text{C}.$$

Aircraft operating at higher altitudes (at or above what is called the transition altitude, which varies by country) set their barometric altimeters to a standard pressure of 29.92 inHg (1 atm = 29.92 inHg) or 1,013.25 hPa (1 hPa = 1 mbar) regardless of the actual sea level pressure, with inches of mercury used in the U.S. and Canada. The resulting altimeter readings are known as flight levels.

Piston engine aircraft with constant-speed propellers also use inches of mercury to measure manifold pressure, which is indicative of engine power produced. In automobile racing, particularly USAC and CART Indy car racing, inches of mercury was the unit used to measure turbocharger inlet pressure.

In older literature, an inch of mercury based on the height of a column at 60 °F (15.6 °C) was common.

$$1 \text{ inHg}_{60 \text{ } ^\circ\text{F}} = 3,376.85 \text{ Pa}$$

In English units: 1 inHg = 0.491098 psi, or 2.036254 inHg = 1 psi.

Inch of water

Inches of water, wc, inch water column (inch WC), inAq, Aq, or inH₂O is a non-SI unit for pressure. The units are by convention and due to the historical measurement of certain pressure differentials. It is used for measuring small pressure differences across an orifice, or in a pipeline or shaft. Inches of water can be converted to a pressure unit using the formula for pressure head.

It is defined as the pressure exerted by a column of water of 1 inch in height at defined conditions for example 39 °F (4 °C) at the standard acceleration of gravity; 1 inAq is approximately equal to 249 pascals at 0 °C.

Alternative standard conditions in common usage are 60 °F, or 68 °F (20 °C), and depends on industry standards rather than on international standards.

In North America, air and other industrial gasses are often measured in inches of water when at low pressure. This is in contrast to inches of mercury or psi for larger pressures. One usage is in the measurement of air ("wind") that supplies a pipe organ and is referred simply as *inches*. It is also used in natural gas distribution for measuring utilization pressure (*U.P.*, i.e. the residential point of use) which is typically between 6 and 7 inches WC (6~7" WC) or about 0.25 psi.

1 inAq = .036126 psi, or 27.68089 inAq = 1 psi.

Kilogram-force per square centimetre



Soviet-made pressure gauges using kgf/cm².

A **kilogram-force per square centimeter** (kgf/cm^2), often just **kilogram per square centimeter** (kg/cm^2), or **kilopond per square centimeter** is a unit of pressure using metric units. Its use is now deprecated; it is not a part of the International System of Units (SI), the modern metric system. Still, kg/cm^2 remains active as a measurement of force primarily due to older torque measurement devices still in use.

In SI units, the unit is converted to the SI derived unit pascal (Pa), which is defined as one newton per square meter (N/m^2). A newton is equal to a $\text{kg}\cdot\text{m/s}^2$, and a kilogram-force is 9.80665 newtons, meaning that 1 kgf/cm^2 equals 98.0665 kilopascals.

In some older publications, **kilogram-force per square centimeter** is abbreviated **ksc** instead of kg/cm^2 .

Technical atmosphere

A **technical atmosphere** (symbol: at) is a non-SI unit of pressure equal to one kilogram-force per square centimeter.

$$1 \text{ at} = 98.0665 \text{ kPa}$$

$$\approx 0.96784 \text{ standard atmospheres}$$

The symbol "at" clashes with that of the katal (symbol: "kat"), the SI unit of catalytic activity; a kilotechnical atmosphere would have the symbol "kat", indistinguishable from the symbol for the katal. It also clashes with that of the non-SI unit, the attotonne, but that unit would be more likely be rendered as the equivalent SI unit, the picogram.

Pressure units						
	Pascal (Pa)	Bar (bar)	Technical atmosphere (at)	Atmosphere (atm)	Torr (Torr)	Pound- force per square inch (psi)
1 Pa	$\equiv 1 \text{ N/m}^2$	10^{-5}	1.0197×10^{-5}	9.8692×10^{-6}	7.5006×10^{-3}	145.04×10^{-6}
1 bar	100,000	$\equiv 10^6 \text{ dyn/cm}^2$	1.0197	0.98692	750.06	14.5037744
1 at	98,066.5	0.980665	$\equiv 1 \text{ kgf/cm}^2$	0.96784	735.56	14.223
1 atm	101,325	1.01325	1.0332	$\equiv 1 \text{ atm}$	760	14.696
1 torr	133.322	1.3332×10^{-3}	1.3595×10^{-3}	1.3158×10^{-3}	$\equiv 1 \text{ Torr};$ $\approx 1 \text{ mmHg}$	19.337×10^{-3}
1	6.894×10^3	68.948×10^{-3}	70.307×10^{-3}	68.046×10^{-3}	51.715	$\equiv 1 \text{ lbf/in}^2$

psi

Example reading: $1 \text{ Pa} = 1 \text{ N/m}^2 = 10^{-5} \text{ bar} = 10.197 \times 10^{-6} \text{ at} = 9.8692 \times 10^{-6} \text{ atm} = 7.5006 \times 10^{-3} \text{ torr} = 145.04 \times 10^{-6} \text{ psi}$
etc.

Copper units of pressure

Copper units of pressure or **CUP**, and the related **lead units of pressure** or **LUP**, are terms applied to pressure measurements used in the field of internal ballistics for the estimation of chamber pressures in firearms. These terms were adopted by convention to indicate that the pressure values were measured by copper crusher and lead crusher gauges respectively. This was necessitated by the adoption of more modern piezoelectric pressure gauges that more accurately measure chamber pressures and generally give significantly higher pressure values. This nomenclature was adopted to avoid confusion and the potentially dangerous interchange of pressure values and standards made by different types of pressure gauges. Pressure is a fundamental thermodynamic parameter that is expressed in units of force divided by area. In the avoirdupois system, the units of pressure are pounds per square inch and in the metric system, the units of pressure are newtons per square meter (pascals). A chamber pressure measured with a copper crusher gauge would be expressed as psi (CUP) in the English system or MPa (CUP) in the metric system.

Methodology

Estimation of pressure using CUP and LUP units is performed by a special *crusher gun*, which uses pressure applied to a piston to crush a carefully manufactured and calibrated copper or lead cylinder. The amount of deformation is compared to the amount of crushing produced by different pressures in pounds per square inch. Copper cylinders are used at high pressures, such as are generated by most handgun and rifle cartridges, and lead cylinders are used for low pressures such as are generated by shotgun shells. The crusher gun has a hole in the chamber that is linked to a piston, and upon firing, this piston is subjected to the pressure of firing. The piston then acts on the calibrated cylinder, crushing it slightly. The length of the crushed cylinder is measured and compared to a chart of lengths resulting from crushing cylinders with given amounts of pressure, and the corresponding force is the CUP or LUP pressure value.

Comparing units

While CUP and LUP numbers were intended to be comparable to the crushing power of a given pressure in psi, the numbers are **not** equivalent. Since a longer duration, lower pressure pulse can crush the cylinder as much as a shorter duration, higher pressure pulse, CUP and LUP pressures frequently register lower than actual peak pressures (as measured by a transducer) by up to 20%. For example, the SAAMI maximum pressure for the 7.62 x 51 mm is given as 52000 psi (CUP), or 62000 psi (430 MPa); the .45-70,

on the other extreme, is listed as 28000 in both CUP and psi (190 MPa). SAAMI standards for a given cartridge may be expressed in CUP units, LUP units, or in standard units of pressure (psi or MPa).

CUP and LUP pressures vs. transducer pressures

Until the invention of measurement transducers in the 1960s, crusher guns were the only reliable method for estimating chamber pressures. With the availability of inexpensive, reliable transducers since the 1960s for actually making chamber pressure measurements, the industry almost universally has begun to move away from crusher guns for estimating chamber pressures, towards favoring making actual measurements. Transducers are also faster to use in practice, as they do not require the careful measuring of the copper or lead cylinders after firing. Additionally, transducers are capable of recording instant-by-instant pressures through the entire firing cycle. Hence, in the long run, using a transducer is less expensive, as it does not require using expendable metal cylinders in a crusher gun, and also reduces the labor required to analyze test results.

One outcome from this transition to using measurement transducers is, for example, that a Speer reloading manual from 1987 lists all SAAMI pressures in CUP, while current references list nearly all pressures in PSI. Another outcome is that design margins are now better determined, which has the effect of increasing the long-term safety of firing multiple thousands of rounds in a gun. With estimates based on crusher guns, actual safety margins could never be accurately assessed, short of actually firing tens of thousands of rounds in a sample gun.

Chapter-9

Newton (unit), Poundal, Pound-force and Planck Force

Newton

Newton

Unit system:	SI derived unit
Unit of...	Force
Symbol:	N
Named after:	Isaac Newton
In SI base units:	$1 \text{ N} = 1 \text{ kg}\cdot\text{m}/\text{s}^2$

The **newton** (symbol: **N**) is the SI derived unit of force, named after Isaac Newton in recognition of his work on classical mechanics.

Definition

The newton is the SI unit for force; it is equal to the amount of net force required to accelerate a mass of one kilogram at a rate of one meter per second squared. In dimensional analysis, $F = ma$, multiplying m (kg) by a (m/s^2), the dimension for 1 newton unit is therefore:

$$\text{N} = \text{kg} \frac{\text{m}}{\text{s}^2} = \text{M} \frac{\text{L}}{\text{T}^2}$$

Examples

- 1 N is the force of Earth's gravity on a mass of about $102 \text{ g} = (1/9.81 \text{ kg})$ (such as a small apple).

- On Earth's surface, a mass of 1 kg exerts a force of approximately 9.8 N [down] (or 1.0 kilogram-force; 1 kgf=9.80665 N by definition). The approximation of 1 kg corresponding to 10 N (1 decanewton or daN) is sometimes used as a rule of thumb in everyday life and in engineering.
- The force of Earth's gravity on a human being with a mass of 70 kg is approximately 686 N.
- The dot product of force and distance is mechanical work. Thus, in SI units, a force of 1 N exerted over a distance of 1 m is 1 N·m of work. The Work-Energy Theorem states that the work done on a body is equal to the change in energy of the body. 1 N·m = 1 J (joule), the SI unit of energy.
- It is common to see forces expressed in kilonewtons or kN, where 1 kN = 1,000 N.

Common use of kilonewtons in construction

Kilonewtons are often used for stating safety holding values of fasteners, anchors and more in the building industry. They are also often used in the specifications for rock climbing equipment. The safe working loads in both tension and shear measurements can be stated in kilonewtons. Injection moulding machines, used to manufacture plastic parts, are classed by kilonewton (i.e., the amount of clamping force they apply to the mould).

On the Earth's surface, 1 kN is about 101.97162 kilograms of load, but multiplying the kilonewton value by 100 (i.e. using a slightly conservative and easier to calculate value) is a good rule of thumb.

Conversion factors

$v \cdot d \cdot e$	Units of force				
	newton (SI unit)	dyne	kilogram- force, kilopond	pound-force	poundal
1 N	$\equiv 1 \text{ kg}\cdot\text{m}/\text{s}^2$	$= 10^5 \text{ dyn}$	$\approx 0.10197 \text{ kp}$	$\approx 0.22481 \text{ lb}_F$	$\approx 7.2330 \text{ pdl}$
1 dyn	$= 10^{-5} \text{ N}$	$\equiv 1 \text{ g}\cdot\text{cm}/\text{s}^2$	$\approx 1.0197 \times 10^{-6} \text{ kp}$	$\approx 2.2481 \times 10^{-6} \text{ lb}_F$	$\approx 7.2330 \times 10^{-5} \text{ pdl}$
1 kp	$= 9.80665 \text{ N}$	$= 980665 \text{ dyn}$	$\equiv g_n \cdot (1 \text{ kg})$	$\approx 2.2046 \text{ lb}_F$	$\approx 70.932 \text{ pdl}$
1 lb_F	$\approx 4.448222 \text{ N}$	$\approx 444822 \text{ dyn}$	$\approx 0.45359 \text{ kp}$	$\equiv g_n \cdot (1 \text{ lb})$	$\approx 32.174 \text{ pdl}$
1 pdl	$\approx 0.138255 \text{ N}$	$\approx 13825 \text{ dyn}$	$\approx 0.014098 \text{ kp}$	$\approx 0.031081 \text{ lb}_F$	$\equiv 1 \text{ lb}\cdot\text{ft}/\text{s}^2$

The value of g_n as used in the official definition of the kilogram-force is used here for all gravitational units.

Four examples of mass and force units

System	FPS Engineering	FPS Gravitational	FPS Absolute	Metric
Force (F)	$F = m \cdot a$	$F = m \cdot a / g_c = w \cdot a / g$	$F = m \cdot a$	$F = m \cdot a$
Weight (w)	$w = m \cdot g$	$w = m \cdot g / g_c \approx m$	$w = m \cdot g$	
Units				
Acceleration (a)	ft/s ²	ft/s ²	ft/s ²	m/s ²
Mass (m)	slug	pound-mass	pound	kilogram
Force (F)	pound	pound-force	poundal	newton

Poundal

The **poundal** (symbol: **pdl**) is a unit of force that is part of the foot-pound-second system of units, in Imperial units introduced in 1879, and is from the specialized subsystem of English Absolut (a coherent system).

The poundal is defined as:

$$pdl = 1 \frac{lb_m \cdot ft}{s^2}$$

or in words, as the force necessary to accelerate 1 pound to 1 foot per second, per second. 1 pdl = 0.138254954376 N exactly.

English units require re-scaling of either force or mass to eliminate a numerical proportionality constant in the equation $\mathbf{F} = \mathbf{ma}$. The poundal represents one choice, which is to rescale units of force. Since a pound of *force* (pound force) accelerates a pound of *mass* (pound mass) at 32.174 049ft/s² (9.80665m/s²; the acceleration of gravity, *g*), we can scale down the unit of force to compensate, giving us one that accelerates 1 pound mass at 1ft/s² rather than at 32.174 049ft/s²; and that is the poundal, which is approximately 1/32 the pounds force.

For example, a force of 1200 poundals is required to accelerate a person of 150 pounds mass at 8 feet per second squared:

$$150lb_m \cdot 8 \frac{ft}{s^2} = 1200pdl$$

The poundal-as-force, pound-as-mass system is contrasted with an alternate system in which pounds are used as *force* (pounds-force), and instead, the *mass* unit is rescaled by a factor of 32. That is, one pound-force will accelerate one pound-mass at 32 feet per second squared; we can scale *up* the unit of *mass* to compensate, which will be accelerated by 1 ft/s² (rather than 32 ft/s²) given the application of one pound force; this

gives us a unit of mass called the slug, which is about 32 pounds mass. Using this system (slugs and pounds-force), the above expression could be expressed as:

$$4.66\text{slug} \cdot 8 \frac{\text{ft}}{\text{s}^2} = 37.3\text{lb}_f$$

Note: Slugs (32.174 049) and poundals (1/32.174 049) are never used in the same system, since each exists to solve the same problem and will cancel each other out; both should not be used together.

Rather than changing either force or mass units, one may choose to express acceleration in units of the acceleration due to Earth's gravity (called g). In this case, we can keep both pounds-mass and pounds-force, such that applying one pound force to one pound mass accelerates it at one unit of acceleration (g):

$$150\text{lb}_m \cdot 0.249g = 37.3\text{lb}_f$$

Expressions derived using poundals for force and lbm for mass (or lb_f for force and slugs for mass) have the advantage of not being tied to conditions on the surface of the earth. Specifically, computing $F=ma$ on the moon or in deep space as poundals = $\text{lb}_m \cdot \text{ft}/\text{s}^2$ or $\text{lb}_f = \text{slug ft}/\text{s}^2$ avoids the constant tied to acceleration of gravity on earth.

Pound-force

The **pound-force** (symbol: lb_F , lb , from Latin *libra* 'pound' and the symbol for force) is a unit of force in systems of measurement including English Engineering units and British Gravitational units. It is equivalent to 4.44822162 newtons. In most contexts, the shorter name "**pound**" is used, but this can introduce confusion with the mass unit of the similar name.

Definitions

The pound-force is equal to the gravitational force exerted on a mass of one avoirdupois pound on the surface of Earth. Since the 18th century, the unit has been used in low-precision measurements, for which small changes in Earth's gravity (which varies from place to place by up to half a percent) can safely be neglected.

The 20th century, however, brought the need for a more precise definition. A standardized value for acceleration due to gravity was therefore needed. Today, in accordance with the General Conference on Weights and Measures, standard gravity is usually taken to be $9.80665 \text{ m}/\text{s}^2$ ($32.174 049 \text{ ft}/\text{s}^2$).

The acceleration of the standard gravitational field (g_n) and the international avoirdupois pound (lb_m) define the pound-force as:

$$\begin{aligned} 1 \text{ lb}_F &= 1 \text{ lb}_m \cdot g_n \\ &= 1 \text{ lb}_m \cdot 32.174049 \frac{\text{ft}}{\text{s}^2} \\ &= 0.45359237 \text{ kg} \cdot 9.80665 \frac{\text{m}}{\text{s}^2} \\ &= 4.44822162 \text{ N} \end{aligned}$$

This definition can be rephrased in terms of the slug, a mass unit equivalent to 32.17405 lb_m . A pound-force is the amount of force required to accelerate a slug at a rate of 1 ft/s^2 , so:

$$1 \text{ lb}_F = 1 \text{ slug} \cdot 1 \frac{\text{ft}}{\text{s}^2}$$

Conversion to other units

	Units of force				
$v \cdot d$ $\cdot e$	newton (SI unit)	dyne	kilogram- force, kilopond	pound-force	poundal
1 N	$\equiv 1 \text{ kg} \cdot \text{m/s}^2$	$= 10^5 \text{ dyn}$	$\approx 0.10197 \text{ kp}$	$\approx 0.22481 \text{ lb}_F$	$\approx 7.2330 \text{ pdl}$
1 dyn	$= 10^{-5} \text{ N}$	$\equiv 1 \text{ g} \cdot \text{cm/s}^2$	$\approx 1.0197 \times 10^{-6} \text{ kp}$	$\approx 2.2481 \times 10^{-6} \text{ lb}_F$	$\approx 7.2330 \times 10^{-5} \text{ pdl}$
1 kp	$= 9.80665 \text{ N}$	$= 980665 \text{ dyn}$	$\equiv g_n \cdot (1 \text{ kg})$	$\approx 2.2046 \text{ lb}_F$	$\approx 70.932 \text{ pdl}$
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1 pdl	$\approx 0.138255 \text{ N}$	$\approx 13825 \text{ dyn}$	$\approx 0.014098 \text{ kp}$	$\approx 0.031081 \text{ lb}_F$	$\equiv 1 \text{ lb} \cdot \text{ft/s}^2$

The value of g_n as used in the official definition of the kilogram-force is used here for all gravitational units.

Foot-pound-second systems of units

In some contexts, the term "pound" is used almost exclusively to refer to the unit of force and not the unit of mass. In those applications, the preferred unit of mass is the slug, i.e. $\text{lb}_f \cdot \text{s}^2/\text{ft}$. In other contexts, the unit "pound" refers to a unit of mass. In circumstances where there may otherwise be ambiguity, the symbols " lb_f " and " lb_m " and the terms "pounds-force" and "pounds-mass" can be used to distinguish.

Four examples of mass and force units

System	FPS Engineering	FPS Gravitational	FPS Absolute	Metric
Force (F)	$F = m \cdot a$	$F = m \cdot a/g_c = w \cdot a/g$	$F = m \cdot a$	$F = m \cdot a$

$$\text{Weight (} w \text{)} \quad w = m \cdot g \quad w = m \cdot g / g_c \approx m \quad w = m \cdot g$$

Units

Acceleration (a)	ft/s ²	ft/s ²	ft/s ²	m/s ²
Mass (m)	slug	pound-mass	pound	kilogram
Force (F)	pound	pound-force	poundal	newton

In the "gravitational" foot-pound-second (fps) system, the weight of the mass unit (pound-mass) on Earth's surface is approximately equal to the force unit (pound-force). The price for this convenience is that the force unit is not equal to the mass unit multiplied by the acceleration unit—the use of Newton's Second Law, $F = m \cdot a$, requires another factor, g_c , usually taken to be $32.17405 \text{ lb} \cdot \text{ft} / (\text{lb}_m \cdot \text{s}^2) = 32.17405 \text{ lb}_m / \text{slug}$. The "engineering" fps system is a *coherent* system of units: by using the slug as the unit of mass, it avoids the need for such a constant. The "absolute" system is similarly coherent; the SI units are those of the "absolute" metric system.

Planck force

Planck force is the derived unit of force resulting from the definition of the base Planck units for time, length, and mass. It is equal to the natural unit of momentum divided by the natural unit of time.

$$F_P = \frac{m_P c}{t_P} = \frac{c^4}{G} = 1.21027 \times 10^{44} \text{ N.}$$

Other derivations

The Planck force is also associated with the equivalence of gravitational potential energy and electromagnetic energy and in this context it can be understood as the force that confines a self-gravitating mass to half its Schwarzschild radius:

$$F_P = \frac{Gm^2}{r_G^2},$$

$$r_G = \frac{r_s}{2} = \frac{Gm}{c^2},$$

where G is the gravitational constant, c is the speed of light, m is any mass and r_G is half the Schwarzschild radius, r_s , of the given mass. Since the dimension of force is also a ratio of energy per length, the Planck force can be calculated as energy divided by half the Schwarzschild radius:

$$F_P = \frac{mc^2}{\frac{Gm}{c^2}} = \frac{c^4}{G}.$$

As mentioned above, Planck force has a unique association with the Planck mass. This unique association also manifests itself when force is calculated as any energy divided by the reduced Compton wavelength (reduced by 2π) of that same energy:

$$F = \frac{mc^2}{\frac{\hbar}{mc}} = \frac{m^2 c^3}{\hbar}.$$

Here the force is different for every mass (for the electron, for example, the force is responsible for the Schwinger effect. It is Planck force only for the Planck mass (approximately 2.18×10^{-8} kg). This follows from the fact that the Planck length is a reduced Compton wavelength equal to half the Schwarzschild radius of the Planck mass:

$$\frac{\hbar}{m_P c} = \frac{G m_P}{c^2}$$

which in turn follows from another relation of fundamental significance:

$$c\hbar = Gm_P^2.$$

General relativity

Planck force is often useful in scientific calculations as a ratio of electromagnetic energy per gravitational length. Thus for example it appears in the Einstein field equations, describing the properties of a gravitational field surrounding any given mass:

$$G_{\mu\nu} = 8\pi \frac{G}{c^4} T_{\mu\nu}$$

where $G_{\mu\nu}$ is the Einstein tensor and $T_{\mu\nu}$ is the energy-momentum tensor.