Handbook of

# Gas and Pneumatics Technologies

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# Chapter 1

# Amine Gas Treating

**Amine gas treating**, also known as **gas sweetening** and **acid gas removal**, refers to a group of processes that use aqueous solutions of various alkylamines (commonly referred to simply as amines) to remove hydrogen sulfide ($H_2S$) and carbon dioxide ($CO_2$) from gases. It is a common unit process used in refineries, and is also used in petrochemical plants, natural gas processing plants and other industries.

Processes within oil refineries or chemical processing plants that remove hydrogen sulfide and/or mercaptans are commonly referred to as ***sweetening*** processes because they result in products which no longer have the sour, foul odors of mercaptans and hydrogen sulfide.

There are many different amines used in gas treating:

- Monoethanolamine (MEA)
- Diethanolamine (DEA)
- Methyldiethanolamine (MDEA)
- Diisopropylamine (DIPA)
- Aminoethoxyethanol (diglycolamine) (DGA)

The most commonly used amines in industrial plants are the alkanolamines MEA, DEA, and MDEA.

Amines are also used in many oil refineries to remove sour gases from liquid hydrocarbons such as liquified petroleum gas (LPG).

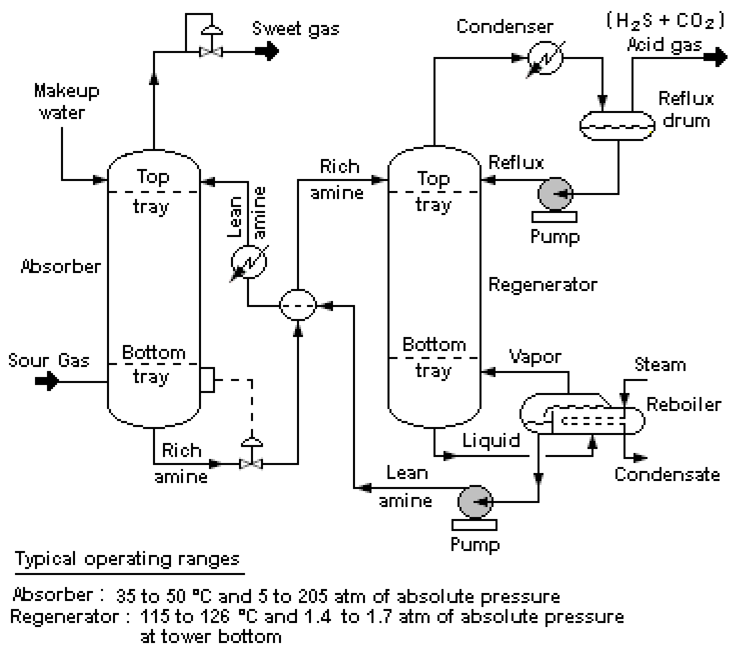
## *Description of a typical amine treater*

Gases containing $H_2S$ or both $H_2S$ and $CO_2$ are commonly referred to as *sour gases* or *acid gases* in the hydrocarbon processing industries.

The chemistry involved in the amine treating of such gases varies somewhat with the particular amine being used. For one of the more common amines, methanolamine (MEA) denoted as $RNH_2$, the chemistry may be simply expressed as:

$$RNH_2 + H_2S \iff RNH_3HS$$

A typical amine gas treating process (as shown in the flow diagram below) includes an **absorber** unit and a **regenerator** unit as well as accessory equipment. In the absorber, the downflowing amine solution absorbs $H_2S$ and $CO_2$ from the upflowing sour gas to produce a sweetened gas stream (i.e., an $H_2S$-free gas) as a product and an amine solution rich in the absorbed acid gases. The resultant "rich" amine is then routed into the regenerator (a stripper with a reboiler) to produce regenerated or "lean" amine that is recycled for reuse in the absorber. The stripped overhead gas from the regenerator is concentrated $H_2S$ and $CO_2$. In oil refineries, that stripped gas is mostly $H_2S$, much of which often comes from a sulfur-removing process called hydrodesulfurization. This $H_2S$-rich stripped gas stream is then usually routed into a Claus process to convert it into elemental sulfur. In fact, the vast majority of the 64,000,000 metric tons of sulfur produced worldwide in 2005 was byproduct sulfur from refineries and other hydrocarbon processing plants. Another sulfur-removing process is the WSA Process which recovers sulfur in any form as concentrated sulfuric acid. In some plants, more than one amine absorber unit may share a common regenerator unit.




Process flow diagram of a typical amine treating process used in industrial plants

The amine concentration in the absorbent aqueous solution is an important parameter in the design and operation of an amine gas treating process. Depending on which one of the following four amines the unit was designed to use and what gases it was designed to remove, these are some typical amine concentrations, expressed as weight percent of pure amine in the aqueous solution:

- Monoethanolamine: About 20 % for removing $H_2S$ and $CO_2$, and about 32 % for removing only $CO_2$.
- Diethanolamine: About 20 to 25 % for removing $H_2S$ and $CO_2$
- Methyldiethanolamine: About 30 to 55% % for removing $H_2S$ and $CO_2$
- Diglycolamine: About 50 % for removing $H_2S$ and $CO_2$

The choice of amine concentration in the circulating aqueous solution depends upon a number of factors and may be quite arbitrary. It is usually made simply on the basis of experience. The factors involved include whether the amine unit is treating raw natural gas or petroleum refinery by-product gases that contain relatively low concentrations of both $H_2S$ and $CO_2$ or whether the unit is treating gases with a very high percentage of $CO_2$ such as the offgas from the steam reforming process used in ammonia production or the flue gases from power plants. Both $H_2S$ and $CO_2$ are acid gases and hence corrosive to carbon steel. However, in an amine treating unit, $CO_2$ is the stronger acid of the two. $H_2S$ forms a film of iron sulfide on the surface of the steel that acts to protect the steel. When treating gases with a very high percentage of $CO_2$, corrosion inhibitors are often used and that permits the use of higher concentrations of amine in the circulating solution. Another factor involved in choosing an amine concentration is the relative solubility of $H_2S$ and $CO_2$ in the selected amine. For more information about selecting the amine concentration, the reader is referred to Kohl and Nielsen's book.

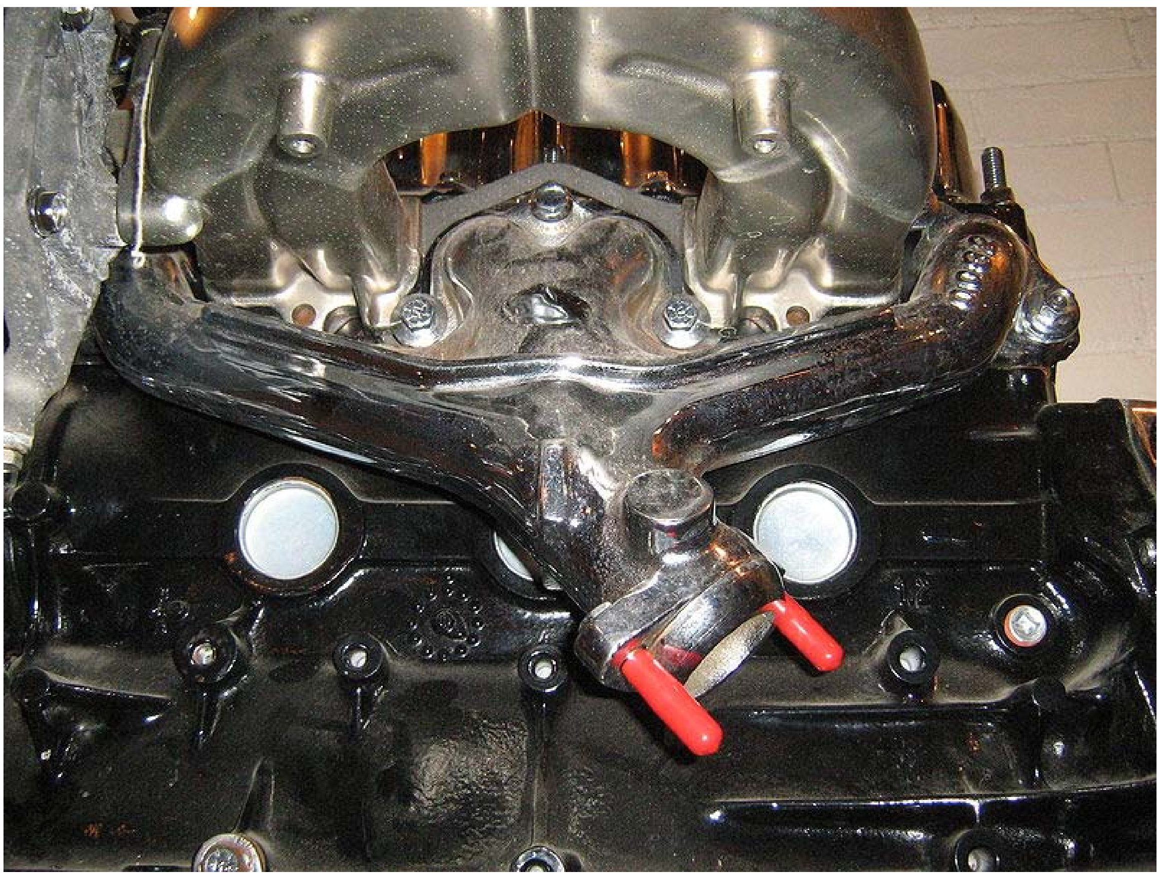
The choice of the type of amine will affect the required circulation rate of amine solution, the energy consumption for the regeneration and the ability to selectively remove either $H_2S$ alone or $CO_2$ alone if desired.

The current emphasis on removing $CO_2$ from the flue gases emitted by fossil fuel power plants has led to much interest in using amines for that purpose.

In the specific case of the industrial synthesis of ammonia, for the steam reforming process of hydrocarbons to produce gaseous hydrogen, amine treating is one of the commonly used processes for removing excess carbon dioxide in the final purification of the gaseous hydrogen.

## Chapter 2

# Exhaust System



Exhaust manifold (chrome plated) on a car engine

Muffler and tail pipe on a car

An **exhaust system** is usually tubing used to guide reaction exhaust gases away from a controlled combustion inside an engine or stove. The entire system conveys burnt gases from the engine and includes one or more **exhaust pipes**. Depending on the overall system design, the exhaust gas may flow through one or more of:

- Cylinder head and exhaust manifold
- A turbocharger to increase engine power.
- A catalytic converter to reduce air pollution.
- A muffler (North America) / silencer (Europe), to reduce noise.

## *Design criteria*

An exhaust pipe must be carefully designed to carry toxic and/or noxious gases away from the users of the machine. Indoor generators and furnaces can quickly fill an enclosed space with carbon monoxide or other poisonous exhaust gases if they are not properly vented to the outdoors. Also, the gases from most types of machine are very hot; the pipe must be heat-resistant, and it must not pass through or near anything which can burn or can be damaged by heat. A chimney serves as an exhaust pipe in a stationary structure. For the internal combustion engine it is important to have the Exhaust System "Tuned" (refer to tuned pipe) for optimal efficiency. Also this should meet the regulation norms maintained in each country.In Europeon countries, EURO 5, India BS-4 etc.,

## Motorcycles

Ducati muffler

In most motorcycles all or most of the exhaust system is visible and may be chrome plated as a display feature. Aftermarket exhausts may be made from steel, aluminium, titanium, or carbon fiber.

Motorcycle exhausts come in many varieties depending on the type of engine and its intended use. A twin cylinder may flow its exhaust into separate exhaust sections, such as seen in the Kawasaki EX250 (also known as the Ninja 250 in the US, or the GPX 250). Or, they may flow into a single exhaust section known as a two-into-one (2-1). Larger engines that come with 4 cylinders, such as Japanese supersport or superbikes (such the Kawasaki ZX series, Honda's CBR series, Yamaha's YZF series, also known as R6 and R1, and Suzuki's GSX-R series) often come with a twin exhaust system. A "full system" may be bought as an aftermarket accessory, also called a 4-2-1 or 4-1, depending on its layout. In the past, these bikes would come standard with a single exhaust, as seen on the Kawasaki ZX-6R 2000 and 2001 models. However, EU noise and pollution regulations have generally stopped this practice, forcing companies to use other methods to increase performance of the motorcycle. This has often led to a decrease in fuel economy, because of increased weight of the exhaust system and manufacturers forcing more fuel into the engine to gain extra power.

## Trucks

In many trucks / lorries all or most of the exhaust system is visible. Often in such trucks the silencer is surrounded by a perforated metal sheath to avoid people getting burnt touching the hot silencer. This sheath may be chrome plated as a display feature. Part of the pipe between the engine and the silencer is often flexible metal industrial ducting, as in the image in the section "Terminology"; this helps to avoid vibration from the engine being transferred into the exhaust system. Sometimes a large diesel exhaust pipe is vertical, to blow the hot noxious gas well away from people; in such cases the end of the exhaust pipe often has a hinged metal flap to stop debris and birds and rainwater from falling inside.

## Two-stroke engines

In a two-stroke engine, such as that used on dirt bikes, a bulge in the exhaust pipe known as an expansion chamber uses the pressure of the exhaust to create a pump that squeezes more air and fuel into the cylinder during the intake stroke. This provides greater power and fuel efficiency.

## Marine engines

With an onboard diesel engine below-decks on marine vessels:-

- Lagging the exhaust pipe stops it from overheating the engine room where people must work to service the engine.
- Feeding water into the exhaust pipe cools the exhaust gas and thus lessens the back-pressure at the engine's cylinders' exhaust ports and thus helps the cylinders to empty quicker.

## Outboard motors

In outboard motors the exhaust system is usually a vertical passage through the engine structure and to reduce out-of-water noise blows out underwater, sometimes through the middle of the propeller.

## *Terminology*

### Manifold or header

Aftermarket exhaust manifold

In most production engines, the **manifold** is an assembly designed to collect the exhaust gas from two or more cylinders into one pipe. Manifolds are often made of cast iron in stock production cars, and may have material-saving design features such as to use the least metal, to occupy the least space necessary, or have the lowest production cost. These design restrictions often result in a design that is cost effective but that does not do the most efficient job of venting the gases from the engine. Inefficiencies generally occur due to the nature of the combustion engine and its cylinders. Since cylinders fire at different times, exhaust leaves them at different times, and pressure waves from gas emerging from one cylinder might not be completely vacated through the exhaust system when another comes. This creates a back pressure and restriction in the engine's exhaust system that can restrict the engine's true performance possibilities.

A **header** (sometimes called **extractor** in Australia) is a manifold specifically designed for performance. During design, engineers create a manifold without regard to weight or cost but instead for optimal flow of the exhaust gases. This design results in a header that is more efficient at **scavenging** the exhaust from the cylinders. Headers are generally circular steel tubing with bends and folds calculated to make the paths from each cylinder's exhaust port to the common outlet all equal length, and joined at narrow angles to encourage pressure waves to flow through the outlet, and not back towards other cylinders. In a set of **tuned headers** the pipe lengths are carefully calculated to enhance exhaust flow in a particular engine revolutions per minute range.

Headers are generally made by aftermarket automotive companies, but sometimes can be bought from the high-performance parts department at car dealerships. Generally, most car performance enthusiasts buy aftermarket headers made by companies solely focused on producing reliable, cost-effective well-designed headers specifically for their car. Headers can also be custom designed by a custom shop. Due to the advanced materials that some aftermarket headers are made of, this can be expensive. Luckily, an exhaust system can be custom built for any car, and generally is not specific to the car's motor or design except for needing to properly connect solidly to the engine. This is usually accomplished by correct sizing in the design stage, and selecting a proper gasket type and size for the engine.

### Header-back

The **Header-back** (or **header back**) is the part of the exhaust system from the outlet of the header to the final vent to open air — everything from the header back. Header-back systems are generally produced as aftermarket performance systems for cars without turbochargers.

### Turbo-back

The **Turbo-back** (or **turbo back**) is the part of the exhaust system from the outlet of a turbocharger to the final vent to open air. Turbo-back systems are generally produced as aftermarket performance systems for cars with turbochargers. Some turbo-back (and header-back) systems replace stock catalytic converters with others having less flow restriction.

### With or without catalytic converter

Some systems (including in former time all systems) (sometimes nowadays called **catless** or **de-cat**) eliminate the catalytic converter. This is illegal in some places if the vehicle is driven on public roads.

### Cat-back

**Cat-back** (also **cat back** and **catback**) refers to the portion of the exhaust system from the outlet of the catalytic converter to the final vent to open air. This generally includes the pipe from the converter to the muffler, the muffler, and the final length of pipe to open air.

Cat-back exhaust systems generally use larger diameter pipe than the stock system. Good systems will have mandrel-bent turns that allow the exhaust gas to exit with as little back pressure as possible. The mufflers included in these kits are often glasspacks, to reduce back pressure. If the system is engineered more for show than functionality, it may be tuned to enhance the lower sounds that are lacking from high-RPM low-displacement engines.

## Tailpipe and exhaust

With trucks, sometimes the silencer is crossways under the front of the cab and its tailpipe blows sideways to the offside (right side if driving on the left, left side if driving on the right). The side of a passenger car on which the exhaust exits beneath the rear bumper usually indicates the market for which the vehicle was designed, i.e. Japanese (and some older British) vehicles have exhausts on the right so they are furthest from the curb in countries which drive on the left, while European vehicles have exhausts on the left.

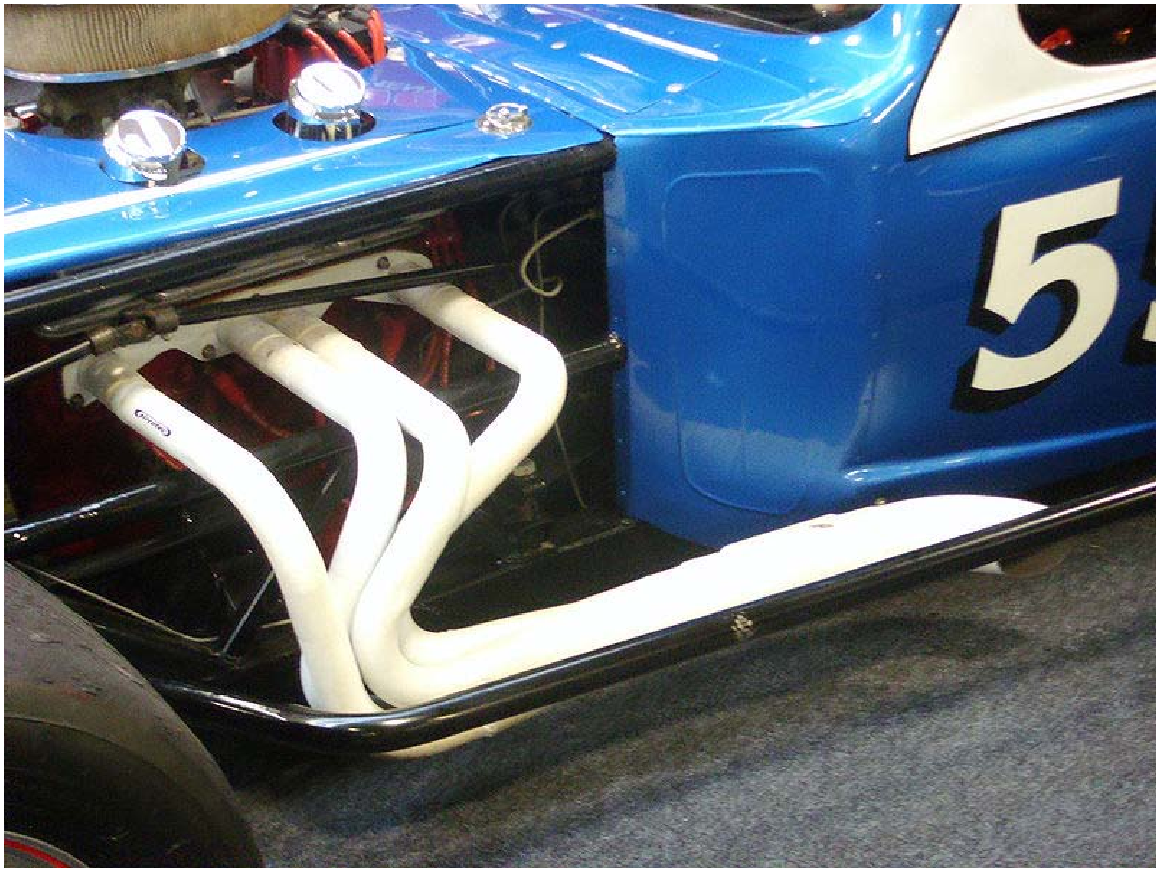
The end of the final length of exhaust pipe where it vents to open air, generally the only visible part of the exhaust system part on a vehicle, often ends with just a straight or angled cut, but may include a fancy tip. The tip is sometimes chromed. It is often of larger pipe than the rest of the exhaust system. This produces a final reduction in pressure, and sometimes used to enhance the appearance of the car.

In the late 1950s in the United States manufacturers had a fashion in car styling to form the rear bumper with a hole at each end through which the exhaust would pass. Two outlets symbolized V-8 power, and only the most expensive cars (Cadillac, Lincoln, Imperial, Packard) were fitted with this design. One justification for this was that luxury cars in those days had such a long rear overhang that the exhaust pipe scraped the ground when the car traversed ramps. The fashion disappeared after customers noted that the rear end of the car, being a low-pressure area, collected soot from the exhaust and its acidic content ate into the chrome-plated rear bumper.

When a bus, truck or tractor or excavator has a vertical exhaust pipe (called stacks or pipes behind the cab), sometimes the end is curved, or has a hinged cover flap which the gas flow blows out of the way, to try to prevent foreign objects (including droppings from a bird perching on the exhaust pipe when the vehicle is not being used) getting inside the exhaust pipe.

In some trucks, when the silencer is front-to-back under the chassis, the end of the tailpipe turns 90° and blows downwards. That protects anyone near a stationary truck from getting a direct blast of the exhaust gas, but often raises dust when the truck is driving on a dry dusty unmade surface such as on a building site.

## *Exhaust System Tuning*



Aftermarket exhaust system including headers and a white plasma-sprayed ceramic coating

Many automotive companies offer aftermarket exhaust system upgrades as a subcategory of engine tuning. This is often fairly expensive as it usually includes replacing the entire exhaust manifold or other large components. These upgrades however can significantly improve engine performance and do this through means of two main principles:

- By reducing the exhaust back pressure, engine power is increased in four-stroke engines
- By reducing the amount of heat from the exhaust being lost into the underbonnet area. This reduces the underbonnet temperature and consequently lowers the intake manifold temperature, increasing power. This also has positive side effect of preventing heat-sensitive components from being damaged. Furthermore, keeping the heat in the exhaust gases speeds these up, therefore reducing back pressure as well.

Back pressure is most commonly reduced by replacing exhaust manifolds with headers, which have smoother bends and normally wider pipe diameters.

Exhaust Heat Management is the term that describes reducing the amount of exhaust heat loss. One dominant solution to aftermarket upgraders is the use of a ceramic coating applied via thermal spraying. This not only reduces heat loss and lessens back pressure, but provides an effective way to protect the exhaust system from wear and tear, thermal degradation and corrosion.

Large truck's diesel exhaust pipe

Waste collection vehicle's diesel exhaust pipe

Dual exhaust pipes attached to a car's muffler

Exhaust system of diesel telescopic-arm vehicle

# Chapter 3

# Gas Detector


Portable gas detector

A **gas detector** is a device which detects the presence of various gases within an area, usually as part of a safety system. This type of equipment is used to detect a gas leak and interface with a control system so a process can be automatically shut down. A gas detector can also sound an alarm to operators in the area where the leak is occurring, giving them the opportunity to leave the area. This type of device is important because there are many gases that can be harmful to organic life, such as humans or animals.

Gas detectors can be used to detect combustible, flammable and toxic gases, and oxygen depletion. This type of device is used widely in industry and can found in a variety of locations such as on oil rigs, to monitor manufacture processes and emerging technologies such as photovoltaic. They may also be used in firefighting.

Gas detectors are usually battery operated. They transmit warnings via a series of audible and visible signals such as alarms and flashing lights, when dangerous levels of gas vapors are detected. As detectors measure a gas concentration, the sensor responds to a calibration gas, which serves as the reference point or scale. As a sensor's detection exceeds a preset alarm level, the alarm or signal will be activated. As units, gas detectors are produced as portable or stationary devices. Originally, detectors were produced to detect a single gas, but modern units may detect several toxic or combustible gases, or even a combination of both types.

## *Types*

Gas detectors come in two main types: portable devices and fixed gas detectors. The first is used to monitor the atmosphere around personnel and is worn on clothing or on a belt/harness. They can also be classified according to the operation mechanism (semiconductors, oxidation, catalytic, infrared, etc.).

## *Oxygen concentration*

Oxygen deficiency gas monitors are used for employee and workforce safety. Cryogenics such as liquid nitrogen (LN2), helium (He), and argon (Ar) are inert and can displace oxygen ($O_2$) in a confined space if a leak is present. A rapid decrease of oxygen can provide a very dangerous environment for employees. With this in mind, an oxygen gas monitor is important to have when cryogenics are present. Laboratories, MRI rooms, pharmaceutical, semiconductor, and cryogenic suppliers are typical customers.

Oxygen fraction in a breathing gas is measured by electro-galvanic fuel cell sensors. They may be used stand-alone, for example to determine the proportion of oxygen in a nitrox mixture used in scuba diving, or as part of feeback loop which maintains a constant partial pressure of oxygen in a rebreather.

## *Hydrocarbons and VOCs*

Detection of hydrocarbons can be based on the mixing properties of gaseous hydrocarbons – or other volatile organic compounds – and the sensing material incorporated in the sensor. The selectivity and sensitivity depends on the molecular structure and concentration; however it is difficult to design a sensor capable of detecting only one single type of molecule.

## *Combustible*

- Catalytic bead sensor

- Explosimeter
- Infrared point sensor
- Infrared open path detector

### *Other*

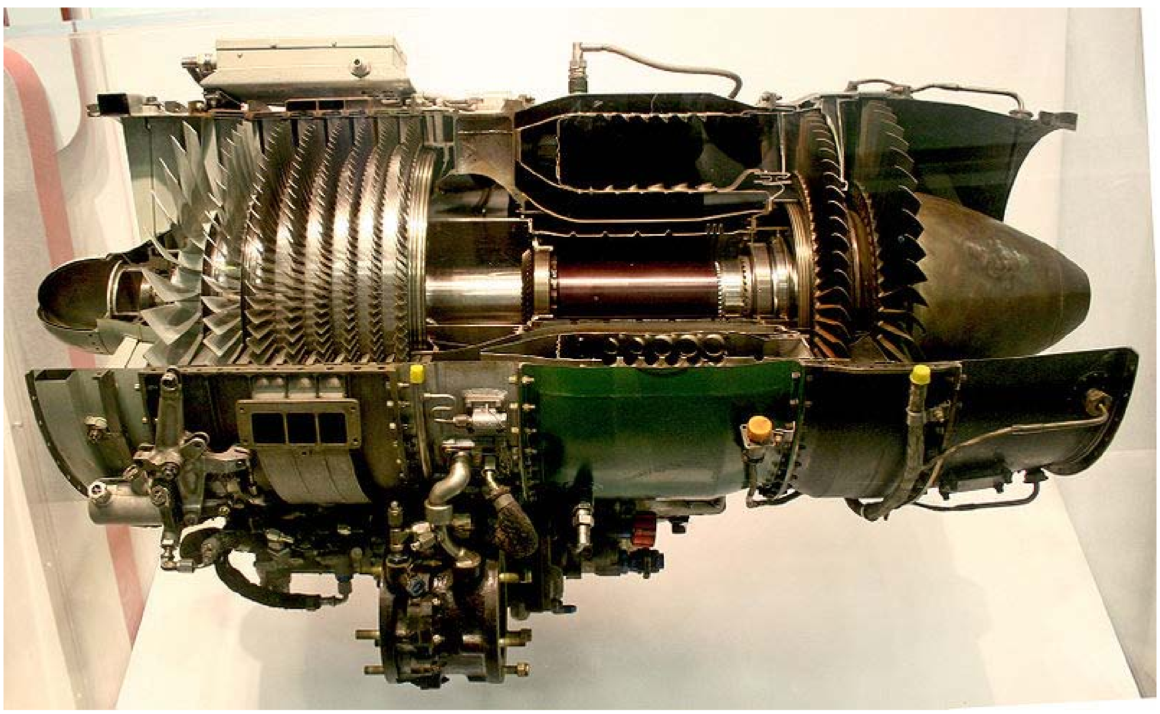
- Flame ionization detector
- Nondispersive infrared sensor
- Photoionization detector
- Zirconium oxide sensor cell
- Catalytic sensors
- Metal oxide semiconductor
- Gold film
- Detector tubes
- Sample collection and chemical analysis
- Piezoelectric microcantilever
- Holographic Sensor
- Thermal Conductivity Detector

### *Manufacturers*

- 3M
- Honeywell Analytics
- Dräger
- Industrial Scientific Corporation
- Linde G-TECTA
- respoRAE

# Chapter 4

# Gas Turbine



A typical axial-flow gas turbine turbojet, the J85, sectioned for display. Flow is left to right, multistage compressor on left, combustion chambers center, two-stage turbine on right

A **gas turbine**, also called a **combustion turbine**, is a rotary engine that extracts energy from a flow of combustion gas. It has an upstream compressor coupled to a downstream turbine, and a combustion chamber in-between. Gas turbine may also refer to just the turbine component.

Energy is added to the gas stream in the combustor, where fuel is mixed with air and ignited. In the high pressure environment of the combustor, combustion of the fuel increases the temperature. The products of the combustion are forced into the turbine section. There, the high velocity and volume of the gas flow is directed through a nozzle over the turbine's blades, spinning the turbine which powers the compressor and, for some turbines, drives their mechanical output. The energy given up to the turbine comes from the reduction in the temperature and pressure of the exhaust gas.

Energy can be extracted in the form of shaft power, compressed air or thrust or any combination of these and used to power aircraft, trains, ships, generators, or even tanks.

## *History*

- 150: Hero's Engine (*aeolipile*) — Apparently, Hero's steam engine was taken to be no more than a toy, and thus its full potential not realized for centuries.
- 1500: The "Chimney Jack" was drawn by Leonardo da Vinci: Hot air from a fire rises through a single-stage axial turbine rotor mounted in the exhaust duct of the fireplace and turning the roasting spit by gear/ chain connection.
- 1551: Taqi al-Din invented a rudimentary form of an impulse steam turbine, which he used to power a self-rotating spit.
- 1629: Jets of steam rotated an impulse turbine that then drove a working stamping mill by means of a bevel gear, developed by Giovanni Branca.
- 1678: Ferdinand Verbiest built a model carriage relying on a steam jet for power.
- 1791: A patent was given to John Barber, an Englishman, for the first true gas turbine. His invention had most of the elements present in the modern day gas turbines. The turbine was designed to power a horseless carriage.
- 1872: A gas turbine engine was designed by Dr. Franz Stolze, but the engine never ran under its own power.
- 1894: Sir Charles Parsons patented the idea of propelling a ship with a steam turbine, and built a demonstration vessel, the *Turbinia*, easily the fastest vessel afloat at the time. This principle of propulsion is still of some use.
- 1895: Three 4-ton 100 kW Parsons radial flow generators were installed in Cambridge Power Station, and used to power the first electric street lighting scheme in the city.
- 1899: Charles Gordon Curtis patented the first gas turbine engine in the USA ("Apparatus for generating mechanical power", Patent No. US635,919).
- 1900: Dr. Sanford Moss submitted a thesis on gas turbines. In 1903, Dr. Moss became an engineer for General Electric's Steam Turbine Department in Lynn, Massachusetts. While there, he applied some of his concepts in the developement of the turbosupercharger. His design used a small turbine wheel, driven by exhaust gases, to turn a supercharger.
- 1903: A Norwegian, Ægidius Elling, was able to build the first gas turbine that was able to produce more power than needed to run its own components, which was considered an achievement in a time when knowledge about aerodynamics was limited. Using rotary compressors and turbines it produced 11 hp (massive for those days). His work was later used by Sir Frank Whittle.
- 1906: The Armengaud-Lemale turbine engine in France with water-cooled combustion chamber.

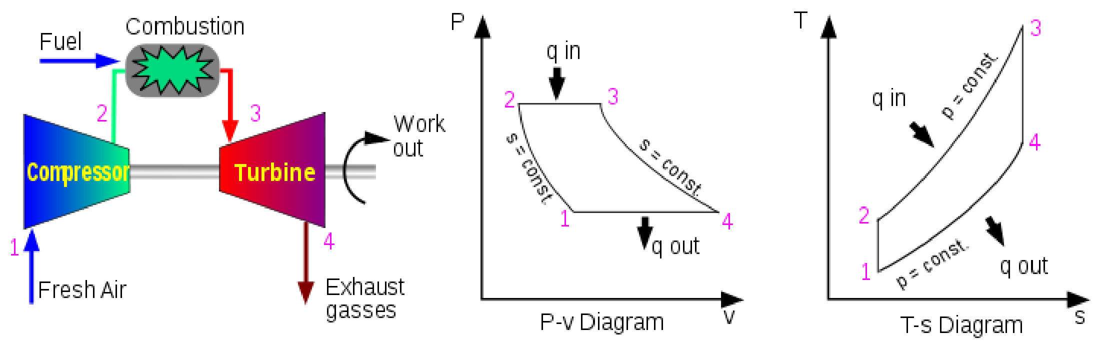
- 1910: Holzwarth impulse turbine (pulse combustion) achieved 150 kilowatts.
- 1913: Nikola Tesla patents the Tesla turbine based on the boundary layer effect.
- 1918: One of the leading gas turbine manufacturers of today, General Electric, started their gas turbine division.
- 1920: The practical theory of gas flow through passages was developed into the more formal (and applicable to turbines) theory of gas flow past airfoils by Dr. A. A. Griffith.
- 1930: Sir Frank Whittle patented the design for a gas turbine for jet propulsion. His work on gas propulsion relied on the work from all those who had previously worked in the same field and he has himself stated that his invention would be hard to achieve without the works of Ægidius Elling. The first successful use of his engine was in April 1937.
- 1932: BBC Brown, Boveri & Cie of Switzerland starts selling axial compressor and turbine turbosets as part of the turbocharged steam generating Velox boiler. Following the gas turbine principle, the steam evaporation tubes are arranged within the gas turbine combustion chamber; the first Velox plant was erected in Mondeville, France.
- 1934: Raúl Pateras de Pescara patented the free-piston engine as a gas generator for gas turbines.
- 1936: Hans von Ohain and Max Hahn in Germany developed their own patented engine design at the same time that Sir Frank Whittle was developing his design in England.
- 1939: First 4 MW utility power generation gas turbine from BBC Brown, Boveri & Cie. for an emergency power station in Neuchâtel, Switzerland.

## *Theory of operation*

Gasses passing through an ideal a gas turbine undergo three thermodynamic processes. These are isentropic compression, isobaric (constant pressure) combustion and isentropic expansion. Together these make up the Brayton cycle.

In a practical gas turbine, gasses are first accelerated in either a centrifugal or radial compressor. These gasses are then slowed using a diverging nozzle known as a diffuser, these process increase the pressure and temperature of the flow. In an ideal system this is isentropic. However, in practice energy is lost to heat, due to friction and turbulence. Gasses then pass from the diffuser to a combustion chamber, or similar device, where heat is added. In an ideal system this occurs at constant pressure (isobaric heat addition). As there is no change in pressure the specific volume of the gasses increases. In practical situations this process is usually accompanied by a slight loss in pressure, due to friction. Finally, this larger volume of gasses is expanded and accelerated by nozzle guide vanes before energy is extracted by a turbine. In an ideal system these are gasses expanded isentropicly and leave the turbine at their original pressure. In practice this process is not isentropic as energy is once again lost to friction and turbulence.

If the device has been designed to power to a shaft as with an industrial generator or a turboprop, the exit pressure will be as close to the entry pressure as possible. In practice it is necessary that some pressure remains at the outlet in order to fully expel the exhaust gasses. In the case of a jet engine only enough pressure and energy is extracted from the flow to drive the compressor and other components. The remaining high pressure gasses are accelerated to provide a jet that can, for example, be used to propel an aircraft.




Brayton cycle

As with all cyclic heat engines, higher combustion temperatures can allow for greater efficiencies. However, temperatures are limited by ability of the steel, nickel, ceramic, or other materials that make up the engine to withstand high temperatures and stresses. To combat this many turbines feature complex blade cooling systems.

As a general rule, the smaller the engine the higher the rotation rate of the shaft(s) needs to be to maintain tip speed. Blade tip speed determines the maximum pressure ratios that can be obtained by the turbine and the compressor. This in turn limits the maximum power and efficiency that can be obtained by the engine. In order for tip speed to remain constant, if the diameter of a rotor is reduced by half, the rotational speed must double. For example large Jet engines operate around 10,000 rpm, while micro turbines spin as fast as 500,000 rpm.

Mechanically, gas turbines can be considerably less complex than internal combustion piston engines. Simple turbines might have one moving part: the shaft/compressor/turbine/alternative-rotor assembly, not counting the fuel system. However, the required precision manufacturing for components and temperature resistant alloys necessary for high efficiency often make the construction of a simple turbine more complicated than piston engines.

More sophisticated turbines (such as those found in modern jet engines) may have multiple shafts (spools), hundreds of turbine blades, movable stator blades, and a vast system of complex piping, combustors and heat exchangers.

Thrust bearings and journal bearings are a critical part of design. Traditionally, they have been hydrodynamic oil bearings, or oil-cooled ball bearings. These bearings are being surpassed by foil bearings, which have been successfully used in micro turbines and auxiliary power units.

## *Types of gas turbines*

### Jet engines

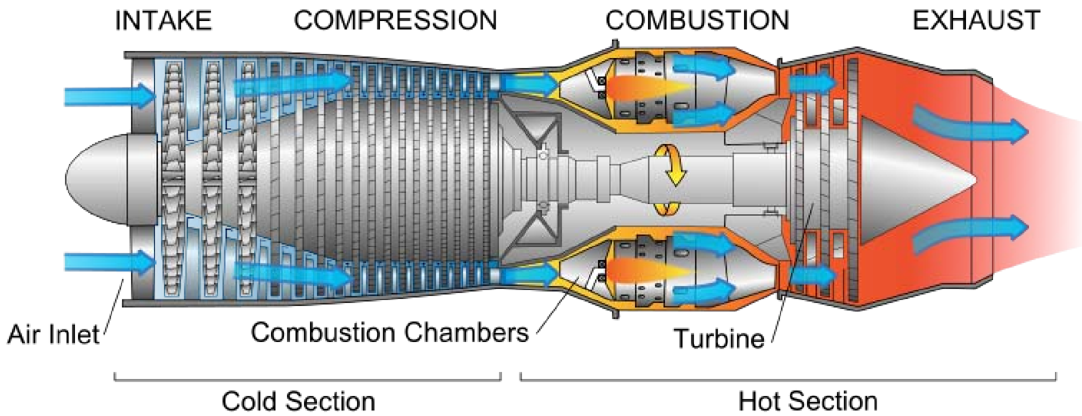



Diagram of a gas turbine jet engine

Airbreathing jet engines are gas turbines optimized to produce thrust from the exhaust gases, or from ducted fans connected to the gas turbines. Jet engines that produce thrust primarily from the direct impulse of exhaust gases are often called turbojets, whereas those that generate most of their thrust from the action of a ducted fan are often called turbofans or (rarely) fan-jets.

Gas turbines are also used in many liquid propellant rockets, the gas turbines are used to power a turbopump to permit the use of lightweight, low pressure tanks, which saves considerable dry mass.

## Aeroderivative gas turbines

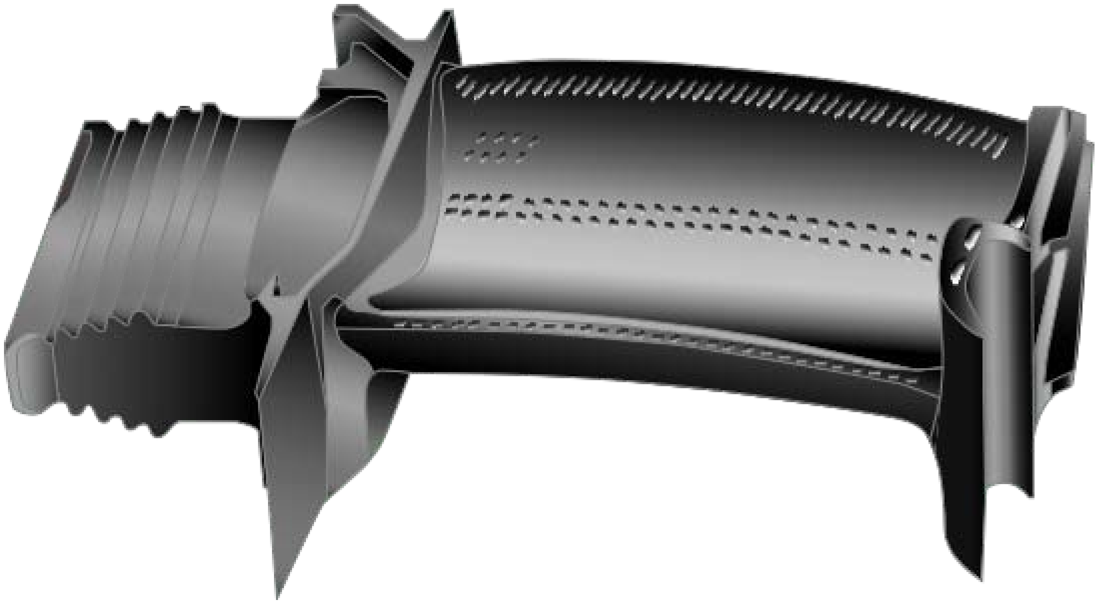


Diagram of a high-pressure turbine blade

Aeroderivatives are also used in electrical power generation due to their ability to startup, shut down, and handle load changes more quickly than industrial machines. They are also used in the marine industry to reduce weight. The General Electric LM2500, General Electric LM6000, Rolls-Royce RB211 and Rolls-Royce Avon are common models of this type of machine.

## Amateur gas turbines

Increasing numbers of gas turbines are being used or even constructed by amateurs.

In its most straightforward form, these are commercial turbines acquired through military surplus or scrapyard sales, then operated for display as part of the hobby of engine collecting. In its most extreme form, amateurs have even rebuilt engines beyond professional repair and then used them to compete for the Land Speed Record.

The simplest form of self-constructed gas turbine employs an automotive turbocharger as the core component. A combustion chamber is fabricated and plumbed between the compressor and turbine sections.

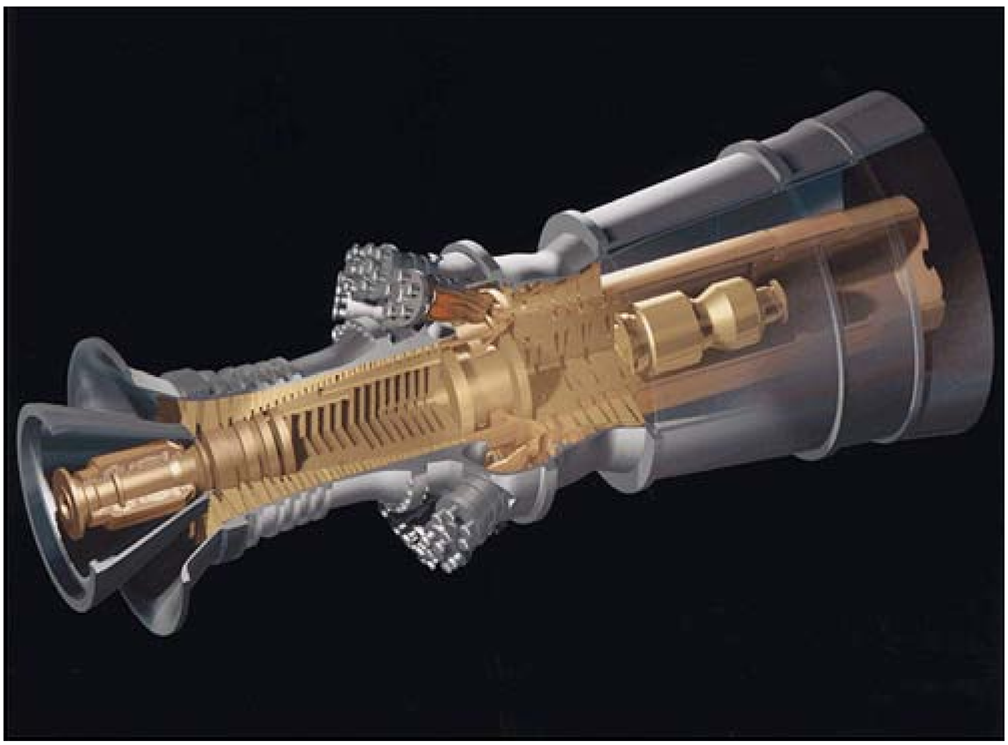
More sophisticated turbojets are also built, where their thrust and light weight are sufficient to power large model aircraft. The Schreckling design constructs the entire engine from raw materials, including the fabrication of a centrifugal compressor wheel from plywood, epoxy and wrapped carbon fibre strands.

Like many technology based hobbies, they tend to give rise to manufacturing businesses over time. Several small companies now manufacture small turbines and parts for the amateur. Most turbojet-powered model aircraft are now using these commercial and semi-commercial microturbines, rather than a Schreckling-like home-build.

## Auxiliary power units

APUs are small gas turbines designed for auxiliary power of larger machines, such as those inside an aircraft. They supply compressed air for aircraft ventilation (with an appropriate compressor design), start-up power for larger jet engines, and electrical and hydraulic power.

## Industrial gas turbines for power generation



GE H series power generation gas turbine: in combined cycle configuration, this 480-megawatt unit has a rated thermal efficiency of 60%.

Industrial gas turbines differ from aeroderivative in that the frames, bearings, and blading is of heavier construction. Industrial gas turbines range in size from truck-mounted mobile plants to enormous, complex systems. They can be particularly efficient—up to 60%—when waste heat from the gas turbine is recovered by a heat recovery steam generator to power a conventional steam turbine in a combined cycle configuration. They can also be run in a cogeneration configuration: the exhaust is used for space or water heating, or drives an absorption chiller for cooling or refrigeration. Such engines require a dedicated enclosure, both to protect the engine from the elements and the operators from the noise.

The construction process for gas turbines can take as little as several weeks to a few months, compared to years for base load power plants. Their other main advantage is the ability to be turned on and off within minutes, supplying power during peak demand. Since single cycle (gas turbine only) power plants are less efficient than combined cycle plants, they are usually used as peaking power plants, which operate anywhere from several hours per day to a few dozen hours per year, depending on the electricity demand and the generating capacity of the region. In areas with a shortage of base load and load following power plant capacity or low fuel costs, a gas turbine power plant may regularly operate during most hours of the day. A large single cycle gas turbine typically produces 100 to 400 megawatts of power and have 35–40% thermal efficiency.

### Compressed air energy storage

One modern development seeks to improve efficiency in another way, by separating the compressor and the turbine with a compressed air store. In a conventional turbine, up to half the generated power is used driving the compressor. In a compressed air energy storage configuration, power, perhaps from a wind farm or bought on the open market at a time of low demand and low price, is used to drive the compressor, and the compressed air released to operate the turbine when required.

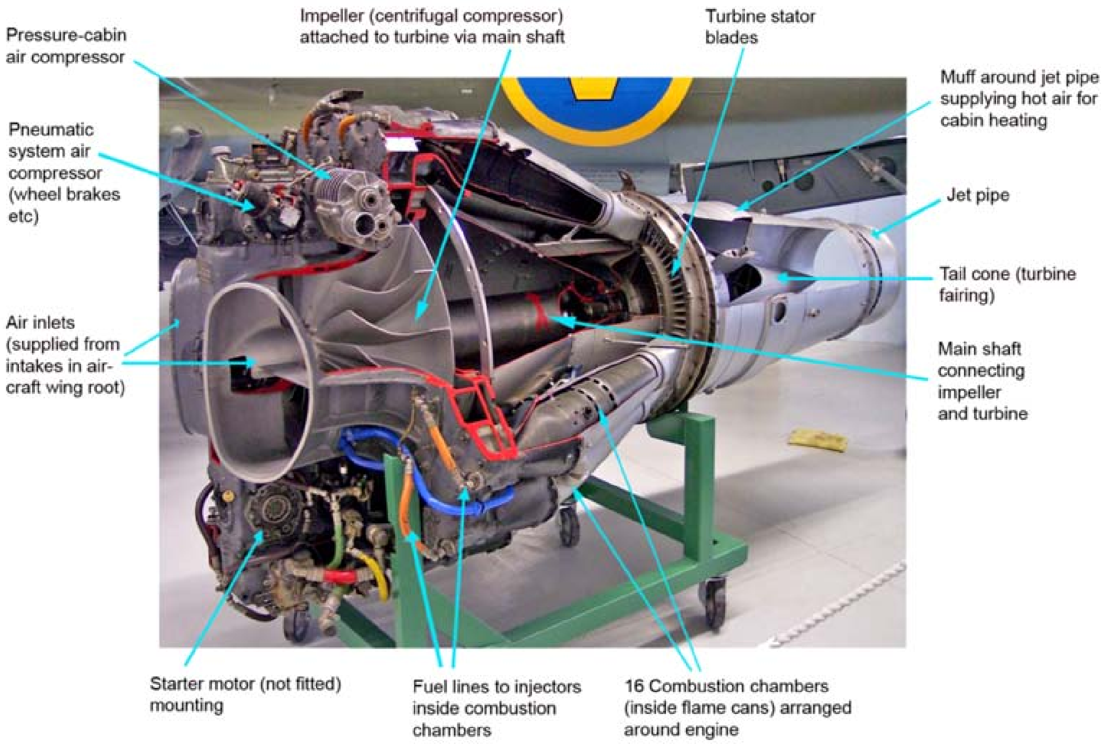
## Turboshaft engines

Turboshaft engines are often used to drive compression trains (for example in gas pumping stations or natural gas liquefaction plants) and are used to power almost all modern helicopters. The first shaft bears the compressor and the high speed turbine (often referred to as "Gas Generator" or "Ng"), while the second shaft bears the low speed turbine (or "Power Turbine" or "Nf" - the 'f' stands for 'free wheeling turbine' on helicopters specifically due to the fact that the gas generator turbine spins separately from the power turbine). This arrangement is used to increase speed and power output flexibility.

## Radial gas turbines

In 1963, Jan Mowill initiated the development at Kongsberg Våpenfabrikk in Norway. Various successors have made good progress in the refinement of this mechanism. Owing to a configuration that keeps heat away from certain bearings the durability of the machine is improved while the radial turbine is well matched in speed requirement.

## Scale jet engines




Scale jet engines are scaled down versions of this early full scale engine

Also known as miniature gas turbines or micro-jets.

With this in mind the pioneer of modern Micro-Jets, Kurt Schreckling, produced one of the world's first Micro-Turbines, the FD3/67. This engine can produce up to 22 newtons of thrust, and can be built by most mechanically minded people with basic engineering tools, such as a metal lathe.

## Microturbines

Also known as:

- Turbo alternators
- MicroTurbine
- Turbogenerator

**Microturbines** are becoming widespread for distributed power and combined heat and power applications. They are one of the most promising technologies for powering hybrid electric vehicles. They range from hand held units producing less than a kilowatt, to commercial sized systems that produce tens or hundreds of kilowatts. Basic principles of microturbine are based on micro combustion.

Part of their success is due to advances in electronics, which allows unattended operation and interfacing with the commercial power grid. Electronic power switching technology eliminates the need for the generator to be synchronized with the power grid. This allows the generator to be integrated with the turbine shaft, and to double as the starter motor.

Microturbine systems have many advantages over reciprocating engine generators, such as higher power-to-weight ratio, low emissions and few, or just one, moving part. Advantages are that microturbines may be designed with foil bearings and air-cooling operating without lubricating oil, coolants or other hazardous materials. Microturbines also have a further advantage of having the majority of the waste heat contained in the relatively high temperature exhaust making it simpler to capture, whereas the waste heat of reciprocating engines is split between its exhaust and cooling system. However, reciprocating engine generators are quicker to respond to changes in output power requirement and are usually slightly more efficient, although the efficiency of microturbines is increasing. Microturbines also lose more efficiency at low power levels than reciprocating engines. When used in extended range electric vehicles the static efficiency drawback is irrelevant, since the gas turbine can be run at or near maximum power, driving an alternator to produce electricity either for the wheel motors, or for the batteries, as appropriate to speed and battery state. The batteries act as a "buffer" (energy storage) in delivering the required amount of power to the wheel motors, rendering throttle response of the GT completely irrelevant. There is, moreover, no need for a significant or variable-speed gearbox; turning an alternator at comparatively high speeds, allows for a smaller and lighter alternator than would otherwise be the case. The superior power-to-weight ratio of the gas turbine and its fixed speed gearbox, allows for a much lighter prime mover than such hybrids as the Toyota Prius (which utilised a 1.8 litre petrol engine) or the Chevrolet Volt (which utilises a 1.4 litre petrol engine). This in turn allows a heavier weight of batteries to be carried. The weight can be made up of more batteries, which allows for a longer electric-only range. Alternatively, the vehicle can use heavier types of batteries such as lead acid batteries (which are cheaper to buy) or safer types of batteries such as Lithium-Iron-Phosphate. When gas turbines are used in extended-range electric vehicles, like those planned by Land-Rover/Range-Rover in conjunction with Bladon, or by Jaguar also in partnership with Bladon, the very poor throttling response (their high moment of rotational inertia) does not matter, because the gas turbine, which may be spinning at 100,000 rpm, is not directly, mechanically connected to the wheels. It was this poor throttling response that so bedevilled the 1960 Rover gas turbine-powered prototype motor car, which did not have the advantage of an intermediate electric drive train.

Gas turbines accept most commercial fuels, such as gasoline, natural gas, propane, diesel, and kerosene as well as renewable fuels such as E85, biodiesel and biogas. However, when running on kerosene or diesel, they will typically be unable to start without the assistance of a more volatile product, such as propane gas.

Microturbine designs usually consist of a single stage radial compressor, a single stage radial turbine and a recuperator. Recuperators are difficult to design and manufacture because they operate under high pressure and temperature differentials. Exhaust heat can be used for water heating, space heating, drying processes or absorption chillers, which create cold for air conditioning from heat energy instead of electric energy.

Typical microturbine efficiencies are 25 to 35%. When in a combined heat and power cogeneration system, efficiencies of greater than 80% are commonly achieved.

MIT started its millimeter size turbine engine project in the middle of the 1990s when Professor of Aeronautics and Astronautics Alan H. Epstein considered the possibility of creating a personal turbine which will be able to meet all the demands of a modern person's electrical needs, just like a large turbine can meet the electricity demands of a small city. Problems have occurred with heat dissipation and high-speed bearing in these new microturbines. Moreover, their expected efficiency is very low 5-6%. According to Professor Epstein current commercial Li-ion rechargeable batteries deliver about 120-150 Wh/kg. MIT's millimeter size turbine will deliver 500-700 Wh/kg in the near term, rising to 1200-1500 Wh/kg in the longer term.

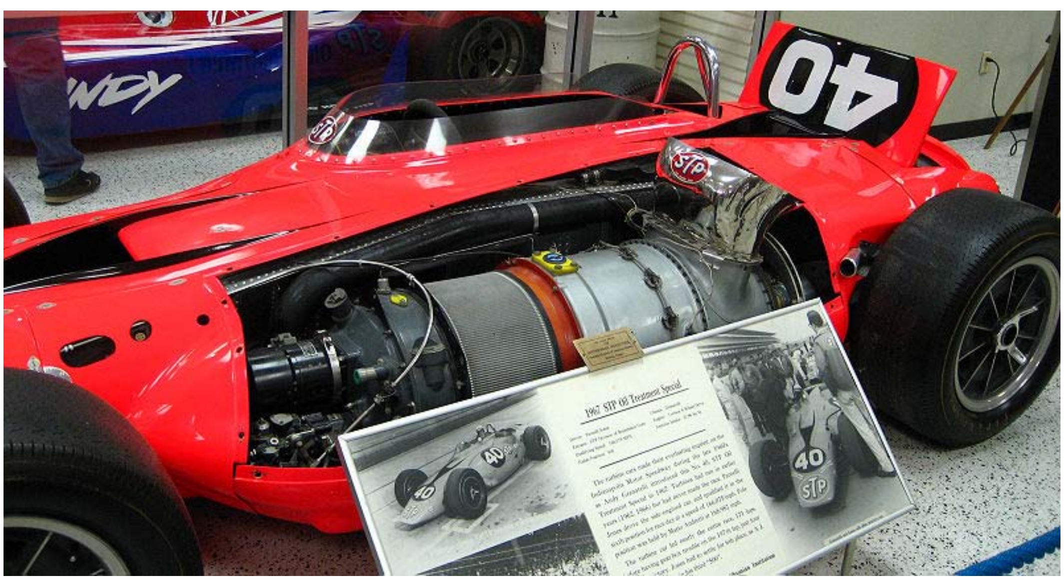
## *External combustion*

Most gas turbines are internal combustion engines but it is also possible to manufacture an external combustion gas turbine which is, effectively, a turbine version of a hot air engine. Those systems are usually indicated as EFGT (Externally Fired Gas Turbine) or IFGT (Indirectly Fired Gas Turbine).

External combustion has been used for the purpose of using pulverized coal or finely ground biomass (such as sawdust) as a fuel. In the indirect system, a heat exchanger is used and only clean air with no combustion products travels through the power turbine. The thermal efficiency is lower in the indirect type of external combustion, however the turbine blades are not subjected to combustion products and much lower quality (and therefore cheaper) fuels are able to be used. Indirectly fired systems are now commercially available. BTOLA, an Australian based company is now marketing 250 kW - 2MW units.

## *Gas turbines in surface vehicles*


The 1950 Rover JET1




The 1967 *STP Oil Treatment Special* on display at the Indianapolis Motor Speedway Hall of Fame Museum, with the Pratt & Whitney gas turbine shown.


A 1968 Howmet TX, the only turbine-powered race car to have won a race.

Gas turbines are often used on ships, locomotives, helicopters, tanks, and to a lesser extent, on cars, buses, and motorcycles.

A key advantage of jets and turboprops for aeroplane propulsion - their superior performance at high altitude compared to piston engines, particularly naturally aspirated ones - is irrelevant in automobile applications. Their power-to-weight advantage, though less critical than for aircraft, is still important.

Gas turbines offer a high-powered engine in a very small and light package. However, they are not as responsive and efficient as small piston engines over the wide range of RPMs and powers needed in vehicle applications. In series hybrid vehicles, as the driving electric motors are mechanically detached from the electricity generating engine, the responsiveness, poor performance at low speed and low efficiency at low output problems are much less important. The turbine can be run at optimum speed for its power output, and batteries and ultracapacitors can supply power as needed, with the engine cycled on and off to run it only at high efficiency. The emergence of the continuously variable transmission may also alleviate the responsiveness problem.

Turbines have historically been more expensive to produce than piston engines, though this is partly because piston engines have been mass-produced in huge quantities for decades, while small gas turbine engines are rarities; however, turbines are mass-produced in the closely related form of the turbocharger.

## Passenger road vehicles (cars, bikes, and buses)

A number of experiments have been conducted with gas turbine powered automobiles, the largest by Chrysler. More recently, there has been some interest in the use of turbine engines for hybrid electric cars. For instance, a consortium led by micro gas turbine company Bladon Jets has secured investment from the Technology Strategy Board to develop an Ultra Lightweight Range Extender (ULRE) for next generation electric vehicles. The objective of the consortium, which includes luxury car maker Jaguar Land Rover and leading electrical machine company SR Drives, is to produce the world's first commercially viable - and environmentally friendly - gas turbine generator designed specifically for automotive applications.

The common turbocharger for gas or diesel engines is also a turbine derivative.

### Concept cars

The first serious mention investigation of using a gas turbine in cars, was in 1946 when two engineers, Robert Kafka and Robert Engerstein of Carney Associates a New York engineering firm, came up with the concept where a unique compact turbine engine design would provide power for a rear wheel drive car. After an article appeared in *Popular Science*, there was no further work, beyond the paper stage.

In 1950, designer F.R. Bell and Chief Engineer Maurice Wilks from British car manufacturers Rover unveiled the first car powered with a gas turbine engine. The two-seater JET1 had the engine positioned behind the seats, air intake grilles on either side of the car, and exhaust outlets on the top of the tail. During tests, the car reached top speeds of 140 km/h (87 mph), at a turbine speed of 50,000 rpm. The car ran on petrol, paraffin or diesel oil, but fuel consumption problems proved insurmountable for a production car. It is on display at the London Science Museum.

American car manufacturer Chrysler demonstrated several prototype gas turbine-powered cars from the early 1950s through the early 1980s. Chrysler built fifty Chrysler Turbine Cars in 1963 and conducted the only consumer trial of gas turbine-powered cars. Their turbines employed unique rotating recuperator that significantly increased efficiency. Chrysler put many cars into the hands of consumers, making this effort a small-scale near-production run.

The original General Motors Firebird was a series of concept cars developed for the 1953, 1956 and 1959 Motorama auto shows, powered by gas turbines.

Toyota demonstrated several gas turbine powered concept cars such as the Century gas turbine hybrid in 1975, the Sports 800 Gas Turbine Hybrid in 1979 and the GTV in 1985. No production vehicles were made. The GT24 engine was exhibited in 1977 without a vehicle.

The fictional Batmobile is often said to be powered by a gas turbine or a jet engine. The 1960s television show vehicle was said to be powered by a turbine engine, with a parachute braking system. For the 1989 *Batman* film, the production department built a working turbine vehicle for the Batmobile prop. Its fuel capacity, however, was reportedly only enough for 15 seconds of use at a time.

In the early 1990s Volvo introduced the Volvo Environmental Concept Car(ECC) which was a gas turbine powered hybrid car.

In 1993 General Motors introduced the first commercial gas turbine powered hybrid vehicle—as a limited production run of the EV-1 series hybrid. A Williams International 40 kW turbine drove an alternator which powered the battery-electric powertrain. The turbine design included a recuperator. Later on in 2006 GM went into the EcoJet concept car project with Jay Leno.

At the 2010 Paris Motor Show Jaguar demonstrated its Jaguar C-X75 concept car. This electrically powered supercar has a top speed of 204 mph (328 km/h) and can go from 0 to 62 mph (0 to 100 km/h) in 3.4 seconds. It uses Lithium-ion batteries to power 4 electric motors which combine to produce some 780 bhp. It will do around 100 miles on a single charge of the batteries but in addition it uses a pair of Bladon Micro Gas Turbines to re-charge the batteries extending the range to some 560 miles.

**Racing cars**

Rover and the BRM Formula One team joined forces to produce the Rover-BRM, a gas turbine powered coupe, which entered the 1963 24 Hours of Le Mans, driven by Graham Hill and Richie Ginther. It averaged 107.8 mph (173 km/h) and had a top speed of 142 mph (229 km/h). American Ray Heppenstall joined Howmet Corporation and McKee Engineering together to develop their own gas turbine sports car in 1968, the Howmet TX, which ran several American and European events, including two wins, and also participated in the 1968 24 Hours of Le Mans. The cars used Continental gas turbines, which eventually set six FIA land speed records for turbine-powered cars.

For open wheel racing, 1967's revolutionary *STP Oil Treatment Special* four-wheel drive turbine-powered special fielded by racing and entrepreneurial legend Andy Granatelli and driven by Parnelli Jones nearly won the Indianapolis 500; the STP Pratt & Whitney powered turbine car was almost a lap ahead of the second place car when a gearbox bearing failed just three laps from the finish line. The next year the STP turbine car won the Indianapolis 500 pole position even though new rules restricted the air intake dramatically. In 1971 Lotus principal Colin Chapman introduced the Lotus 56B F1 car, powered by a Pratt & Whitney gas turbine. Chapman had a reputation of building radical championship-winning cars, but had to abandon the project because there were too many problems with turbo lag.

**Buses**

The arrival of the Capstone Microturbine has led to several hybrid bus designs, starting with HEV-1 by AVS of Chattanooga, Tennessee in 1999, and closely followed by Ebus and ISE Research in California, and DesignLine Corporation in New Zealand (and later the United States). AVS turbine hybrids were plagued with reliability and quality control problems, resulting in liquidation of AVS in 2003. The most successful design by Designline is now operated in 5 cities in 6 countries, with over 30 buses in operation worldwide, and order for several hundred being delivered to Baltimore , and NYC.

Brescia Italy is using serial hybrid buses powered by microturbines on routes through the historical sections of the city.

**Motorcycles**

The MTT Turbine SUPERBIKE appeared in 2000 (hence the designation of Y2K Superbike by MTT) and is the first production motorcycle powered by a turbine engine - specifically, a Rolls-Royce Allison model 250 turboshaft engine, producing about 283 kW (380 bhp). Speed-tested to 365 km/h or 227 mph (according to some stories, the testing team ran out of road during the test), it holds the Guinness World Records for most powerful production motorcycle and most expensive production motorcycle, with a price tag of US$185,000.

## Trains

Several locomotive classes have been powered by gas turbines, the most recent incarnation being Bombardier's JetTrain.

## Tanks

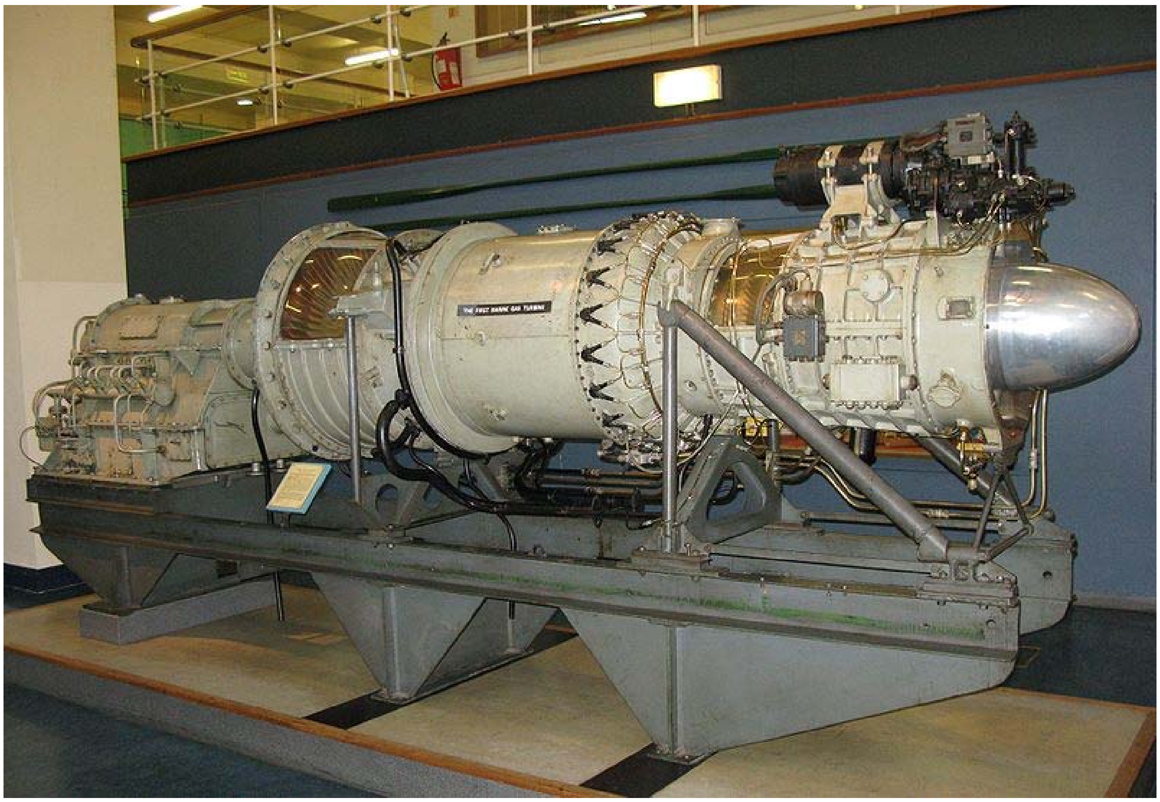
Marines from 1st Tank Battalion load a Honeywell AGT1500 multi-fuel turbine back into the tank at Camp Coyote, Kuwait, February 2003.

The German Army's development division, the Heereswaffenamt (Army Ordnance Board), studied a number of gas turbine engines for use in tanks starting in mid-1944. The first gas turbine engines used for armoured fighting vehicle GT 101 was installed in Panther tank. The second use of a gas turbine in an armoured fighting vehicle was in 1954 when a unit, PU2979, specifically developed for tanks by C. A. Parsons & Co., was installed and trialled in a British Conqueror tank. The Stridsvagn 103 was developed in the 1950s and was the first mass produced main battle tank to use a turbine engine. Since then, gas turbine engines have been used as APUs in some tanks and as main powerplants in Soviet/Russian T-80s and U.S. M1 Abrams tanks, among others. They are lighter and smaller than diesels at the same sustained power output but the models installed to date are less fuel efficient than the equivalent diesel, especially at idle, requiring more fuel to achieve the same combat range. Successive models of M1 have addressed this problem with battery packs or secondary generators to power the tank's systems while stationary, saving fuel by reducing the need to idle the main turbine. T-80s can mount three large external fuel drums to extend their range. Russia has stopped production of the T-80 in favour of the diesel-powered T-90 (based on the T-72), while Ukraine has developed the diesel-powered T-80UD and T-84 with nearly the power of the gas-turbine tank.

A turbine is theoretically more reliable and easier to maintain than a piston engine, since it has a simpler construction with fewer moving parts but in practice turbine parts experience a higher wear rate due to their higher working speeds. The turbine blades are highly sensitive to dust and fine sand, so that in desert operations air filters have to be fitted and changed several times daily. An improperly fitted filter, or a bullet or shell fragment that punctures the filter can damage the engine. Piston engines also need well-maintained filters, but they are more resilient if the filter does fail.

Like most modern diesel engines used in tanks, gas turbines are usually multi-fuel engines.

### Naval



The Gas turbine from MGB 2009

Gas turbines are used in many naval vessels, where they are valued for their high power-to-weight ratio and their ships' resulting acceleration and ability to get underway quickly.

The first gas-turbine-powered naval vessel was the Royal Navy's Motor Gun Boat *MGB 2009* (formerly *MGB 509*) converted in 1947. Metropolitan-Vickers developed the "Beryl" engine equipping an existing F2/3 jet engine with a power turbine. As the test was successful, the Fast Patrol Boats *Bold Pioneer* and *Bold Pathfinder* built in 1953 were the first ships created specifically for gas turbine propulsion.

The first large scale, gas-turbine powered ships, were the Royal Navy's Type 81 (Tribal class) frigates, the first of which (HMS *Ashanti*) was commissioned in 1961.

The Germany Navy launched the first Köln class frigate in 1961 with 2 GTs from BBC in the worlds first combined diesel and gas propulsion system.

The Swedish Navy produced 6 Spica class torpedoboats between 1966 and 1967 powered by 3 Bristol Siddeley Proteus 1282, each delivering 4300 hp. They were later joined by 12 upgraded Norrköping class ships, still with the same engines. With their aft torpedo tubes replaced by antishipping missiles they served as missile boats until the last was retired in 2005.

The Finnish Navy issued two Turunmaa class corvettes, Turunmaa and Karjala, in 1968. They were equipped with one 22,000 shp Rolls-Royce Olympus TMB3 gas turbine and three Wärtsilä marine diesels for slower speeds. They were the fastest vessels in the Finnish Navy; they regularly achieved 35 knot speeds, with 37.3 knots on sea trials. The Turunmaas were paid off in 2002. *Karjala* is today a museum ship in Turku, and *Turunmaa* serves as a floating machine shop and training ship for Satakunta Polytechnical College.

The next series of major naval vessels were the four Canadian Iroquois class helicopter carrying destroyers first commissioned in 1972. They used 2 ft-4 main propulsion engines, 2 ft-12 cruise engines and 3 Solar Saturn 750 kW generators.

The first U.S. gas-turbine powered ships were the U.S. Coast Guard's *Hamilton*-class High Endurance Cutters the first of which (USCGC *Hamilton*) commissioned in 1967. Since then, they have powered the U.S. Navy's *Perry*-class frigates, *Spruance*-class and *Arleigh Burke*-class destroyers, and *Ticonderoga*-class guided missile cruisers. USS *Makin Island*, a modified *Wasp*-class amphibious assault ship, is to be the Navy's first amphibious assault ship powered by gas turbines. The marine gas turbine operates in a more corrosive atmosphere due to presence of sea salt in air and fuel and use of cheaper fuels.

## Maritime

There have been a number of experiments in which gas turbines were used to power seagoing commercial vessels. The earliest of these experiments may have been the oil tanker "Auris" (Anglo Saxon Petroleum) - circa 1949.

The United States Maritime Commission were looking for options to update WWII Liberty ships and heavy duty gas turbines were one of those selected. In 1956 the "John Sergeant" was lengthened and installed with a General Electric 6600 SHP HD gas turbine, reduction gearing and a variable pitch propeller. It operated for 9700 hours using residual fuel for 7000 hours. The success of this trial opened the way for more development by GE on the use of HD gas turbines for marine use with heavy fuels. The "John Sergeant" was scrapped in 1972 at Portsmouth PA.

Boeing launched its first passenger-carrying waterjet-propelled hydrofoil Boeing 929, in April 1974. Those ships were powered by twin Allison gas turbines of the KF-501 series.

Between 1970 and 1982, Seatrain Container Lines operated a scheduled container service across the North Atlantic with four 26,000 tonne dwt. container ships. Those ships were powered by twin Pratt & Whitney gas turbines of the FT 4 series. The four ships in the class were named "Euroliner", "Eurofreighter", "Asialiner" and "Asiafreighter". They operated a transatlantic container service between ports on the eastern seaboard of the United States and ports in north west Europe. Following the dramatic OPEC(Organization of the Petroleum Exporting Countries) price increases of the mid-nineteen seventies, operations were constrained by rising fuel costs. Some modification of the engine systems on those ships was undertaken to permit the burning of a lower grade of fuel (i.e., marine diesel). The modifications were partially successful. It was proved that particular fuel could be used in a marine gas turbine but, savings made were less than anticipated due to increased maintenance requirements. After 1982 the ships were sold, then re-engined with more economical diesel engines. Because the new engines were much larger, there was a consequential loss of some cargo space.

The first passenger ferry to use a gas turbine was the GTS *Finnjet*, built in 1977 and powered with two Pratt & Whitney FT 4C-1 DLF turbines, generating 55 MW and propelling the ship to a speed of 31 knots. However, the Finnjet also illustrated the shortcomings of gas turbine propulsion in commercial craft, as high fuel prices made operating her unprofitable. After just four years of service additional diesel engines were installed on the ship to allow less costly operations during off-season. Another example of commercial usage of gas turbines in a passenger ship are Stena Line's HSS class fastcraft ferries. HSS 1500-class *Stena Explorer*, *Stena Voyager* and *Stena Discovery* vessels use COGAG setups of twin GE LM2500 plus GE LM1600 power for a total of 68 MW. The slightly smaller HSS 900-class *Stena Charisma*, uses twin ABB–STAL GT35 turbines rated at 34,000 kW gross. The *Stena Discovery* was withdrawn from service in 2007, another victim of too high fuel costs.

In July 2000, the Millennium became the first cruise ship to be propelled by gas turbines, in a Combined Gas and Steam Turbine configuration. The RMS Queen Mary 2 uses a Combined Diesel and Gas Turbine configuration.

### *Advances in technology*

Gas turbine technology has steadily advanced since its inception and continues to evolve; research is active in producing ever smaller gas turbines. Computer design, specifically CFD and finite element analysis along with material advances, has allowed higher compression ratios and temperatures, more efficient combustion and better cooling of engine parts. On the emissions side, the challenge in technology is increasing turbine inlet temperature while reducing peak flame temperature to achieve lower NOx emissions to cope with the latest regulations. Additionally, compliant foil bearings were commercially introduced to gas turbines in the 1990s. They can withstand over a hundred thousand start/stop cycles and eliminated the need for an oil system.

On another front, microelectronics and power switching technology have enabled commercially viable micro turbines for distributed and vehicle power.

## *Advantages and disadvantages of gas turbine engines*

Reference for this section:

### Advantages of gas turbine engines

- Very high power-to-weight ratio, compared to reciprocating engines;
- Smaller than most reciprocating engines of the same power rating.
- Moves in one direction only, with far less vibration than a reciprocating engine.
- Fewer moving parts than reciprocating engines.
- Low operating pressures.
- High operation speeds.
- Low lubricating oil cost and consumption.
- Can run on a wide variety of fuels.

### Disadvantages of gas turbine engines

- Cost
- Less efficient than reciprocating engines at idle
- Longer startup than reciprocating engines
- Less responsive to changes in power demand compared to reciprocating engines

## Chapter 5

# Piping and Pneumatics

## Piping


Large-scale piping system in an HVAC mechanical room

Within industry, **piping** is a system of pipes used to convey fluids (liquids and gases) from one location to another. The engineering discipline of piping design studies the efficient transport of fluid.

Industrial process piping (and accompanying in-line components) can be manufactured from wood, fiberglass, glass, steel, aluminum, plastic, copper, and concrete. The in-line components, known as fittings, valves, and other devices, typically sense and control the pressure, flow rate and temperature of the transmitted fluid, and usually are included in the field of Piping Design (or Piping Engineering). Piping systems are documented in piping and instrumentation diagrams (P&IDs). If necessary, pipes can be cleaned by the tube cleaning process.

"Piping" sometimes refers to Piping Design or the performance of the actual layout of the physical piping within a process plant or commercial building. In earlier days, this was sometimes called Drafting, Technical drawing, Engineering Drawing, and Design but is commonly performed by Designers who have learned to used automated computer aided drawing/computer aided design (CAD) software.

Plumbing is a piping system that most people are familiar with, as it constitutes the form of fluid transportation that is used to provide potable water and fuels to their homes and business. Plumbing pipes also remove waste in the form of sewage, and allow venting of sewage gases to the outdoors. Fire sprinkler systems also use piping, and may transport potable or nonpotable water, or other fire-suppression fluids.

Piping also has many other industrial applications, which are crucial for moving raw and semi-processed fluids for refining into more useful products. Some of the more exotic materials of construction are Inconel, Titanium, chrome-moly and various other steel alloys.

## *Piping Branches*

Generally, Industrial piping has three major branches as follows:

- Piping Material field
- Piping Design field
- Stress analysis field

## *Pipe stress analysis*

Process piping and power piping are typically checked by pipe stress engineers to verify that the routing, nozzle loads, hangers, and supports are properly placed and selected such that allowable pipe stress is not exceeded under different situation such as sustain, operating, hydro test etc as per the ASME or any other legislative code and local government standards. It is necessary to evaluate the mechanical behavior of the piping under regular loads (internal pressure and thermal stresses) as well under occasional and intermittent loading cases such as earthquake, high wind or special vibration, water hammer. This evaluation is usually performed with the assistance of a specialized (finite element) pipe stress analysis computer program such as Caesar II, ROHR2, CAEPIPE and AUTOPIPE.

### Wooden piping history

Early wooden pipes were constructed out of logs that had a large hole bored lengthwise through the center. Later wooden pipes were constructed with staves and hoops similar to wooden barrel construction. Stave pipes have the advantage that they are easily transport as a compact pile of parts on a wagon and then assembled as a hollow structure at the job site. Wooden pipes were especially popular in mountain regions where transport of heavy iron or concrete pipes would have been difficult.

Wooden pipes were easier to maintain than metal, because the wood did not expand or contract with temperature changes as much as metal and so consequently expansion joints and bends were not required. The thickness of wood afforded some insulating properties to the pipes which helped prevent freezing as compared to metal pipes. Wood used for water pipes also does not rot very easily. Electrolysis that bugbear many iron pipe systems, doesn't affect wood pipes at all, since wood is a much better electrical insulator.

In the Western United States where redwood was used for pipe construction, it was found that redwood had "peculiar properties" that protected it from weathering, acids, insects, and fungus growths. Redwood pipes stayed smooth and clean indefinitely while iron pipe by comparison would rapidly begin to scale and corrode and could eventually plug itself up with the corrosion.

# Pneumatics

Preserved Porter Locomotive Company No. 3290 of 1923.

**Pneumatics** is a branch of technology, which deals with the study and application of use of pressurized gas to affect mechanical motion.

Pneumatic systems are extensively used in industry, where factories are commonly plumbed with compressed air or other compressed inert gases. This is because a centrally-located and electrically-powered compressor that powers cylinders and other pneumatic devices through solenoid valves is often able to provide motive power in a cheaper, safer, more flexible, and more reliable way than a large number of electric motors and actuators.

Pneumatics also has applications in dentistry, construction, mining, and other areas.

## *Examples of pneumatic systems and components*

- Air brakes on buses and trucks
- Air brakes, on trains
- Air compressors
- Air engines for pneumatically powered vehicles
- Barostat systems used in Neurogastroenterology and for researching electricity
- Cable jetting, a way to install cables in ducts
- Compressed-air engine and compressed-air vehicles

- Gas-operated reloading
- Holman Projector, a pneumatic anti-aircraft weapon
- Lego pneumatics can be used to build pneumatic models

- Pipe organs:
    - Electro-pneumatic action
    - Tubular-pneumatic action

- Pneumatic actuator
- Pneumatic air guns
- Pneumatic cylinder
- Pneumatic Launchers, a type of spud gun
- Pneumatic mail systems
- Pneumatic motor
- Pneumatic tire

- Pneumatic tools:
    - Jackhammer used by road workers
    - Pneumatic nailgun

- Pressure regulator
- Pressure sensor
- Pressure switch

- Vacuum pump

## *Gases used in pneumatic systems*

Pneumatic systems in fixed installations such as factories use compressed air because a sustainable supply can be made by compressing atmospheric air. The air usually has moisture removed and a small quantity of oil added at the compressor, to avoid corrosion of mechanical components and to lubricate them.

Factory-plumbed, pneumatic-power users need not worry about poisonous leakages as the gas is commonly just air. Smaller or stand-alone systems can use other compressed gases which are an asphyxiation hazard, such as nitrogen - often referred to as OFN (oxygen-free nitrogen), when supplied in cylinders.

Any compressed gas other than air is an asphyxiation hazard - including nitrogen, which makes up 77% of air. Compressed oxygen (approx. 23% of air) would not asphyxiate, but it would be an extreme fire hazard, so is never used in pneumatically powered devices.

Portable pneumatic tools and small vehicles such as Robot Wars machines and other hobbyist applications are often powered by compressed carbon dioxide because containers designed to hold it such as soda stream canisters and fire extinguishers are readily available, and the phase change between liquid and gas makes it possible to obtain a larger volume of compressed gas from a lighter container than compressed air would allow. Carbon dioxide is an asphyxiant and can also be a freezing hazard when vented inappropriately.

## *Comparison to hydraulics*

Both pneumatics and hydraulics are applications of fluid power. Pneumatics uses an easily compressible gas such as air or a suitable pure gas, while hydraulics uses relatively incompressible liquid media such as oil. Most industrial pneumatic applications use pressures of about 80 to 100 pounds per square inch (550 to 690 kPa). Hydraulics applications commonly use from 1,000 to 5,000 psi (6.9 to 34 MPa), but specialized applications may exceed 10,000 psi (69 MPa).

### Advantages of pneumatics

- **Simplicity of Design And Control**
    - Machines are easily designed using standard cylinders & other components. Control is as easy as it is simple ON - OFF type control.
- **Reliability**
    - Pneumatic systems tend to have long operating lives and require very little maintenance.
    - Because gas is compressible, the equipment is less likely to be damaged by shock. The gas in pneumatics absorbs excessive force, whereas the fluid of hydraulics directly transfers force.
- **Storage**
    - Compressed Gas can be stored, allowing the use of machines when electrical power is lost.
- **Safety**
    - Very low chance of fire (compared to hydraulic oil).
    - Machines can be designed to be overload safe.

### Advantages of hydraulics

- Liquid (as a gas is also a 'fluid') does not absorb any of the supplied energy.
- Capable of moving much higher loads and providing much higher forces due to the incompressibility.
- The hydraulic working fluid is basically incompressible, leading to a minimum of spring action. When hydraulic fluid flow is stopped, the slightest motion of the load releases the pressure on the load; there is no need to "bleed off" pressurized air to release the pressure on the load.

## *Pneumatic logic*

Pneumatic logic systems (sometimes called **air logic control**) are often used to control industrial processes, consisting of primary logic units such as:

- And Units
- Or Units
- 'Relay or Booster' Units
- Latching Units
- 'Timer' Units
- Sorteberg relay
- fluidics amplifiers with no moving parts other than the air itself

Pneumatic logic is a reliable and functional control method for industrial processes. In recent years, these systems have largely been replaced by electrical control systems, due to the smaller size and lower cost of electrical components. Pneumatic devices are still used in processes where compressed air is the only energy source available or upgrade cost, safety, and other considerations outweigh the advantage of modern digital control.

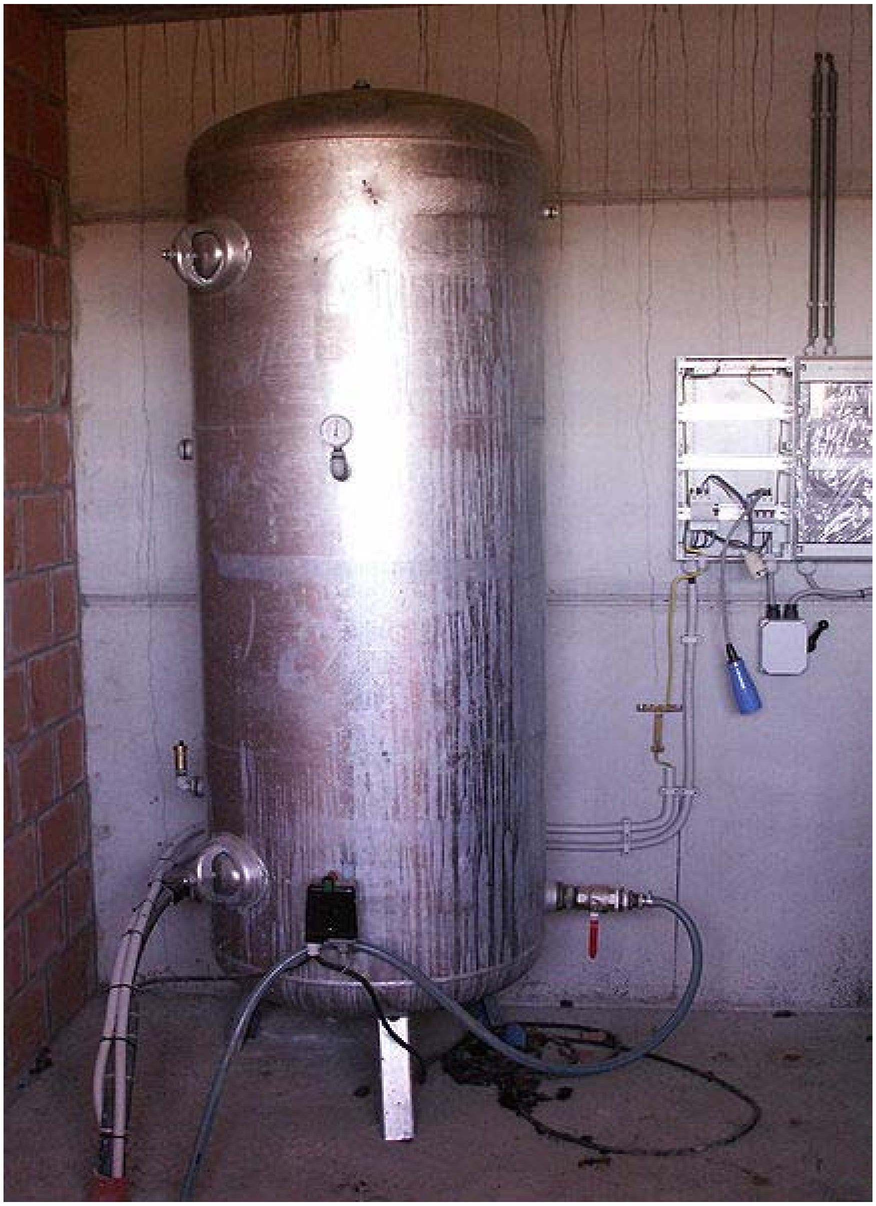
# Chapter 6

# Pressure Vessel

A **pressure vessel** is a closed container designed to hold gases or liquids at a pressure substantially different from the ambient pressure.

The pressure differential is dangerous and many fatal accidents have occurred in the history of their development and operation. Consequently, their design, manufacture, and operation are regulated by engineering authorities backed up by laws. For these reasons, the definition of a pressure vessel varies from country to country, but involves parameters such as maximum safe operating pressure and temperature.

### *Uses*



A pressure tank connected to a water well and domestic hot water system

A few pressure tanks, here used to hold propane

Pressure vessels are used in a variety of applications in both industry and the private sector. They appear in these sectors as industrial compressed air receivers and domestic hot water storage tanks. Other examples of pressure vessels are diving cylinder, recompression chamber, distillation towers, autoclaves, and many other vessels in mining or oil refineries and petrochemical plants, nuclear reactor vessel, habitat of a space ship, habitat of a submarine, pneumatic reservoir, hydraulic reservoir under pressure, rail vehicle airbrake reservoir, road vehicle airbrake reservoir and storage vessels for liquified gases such as ammonia, chlorine, propane, butane, and LPG.

### *Shape of a pressure vessel*

Pressure vessels may theoretically be almost any shape, but shapes made of sections of spheres, cylinders, and cones are usually employed. A common design is a cylinder with end caps called heads. Head shapes are frequently either hemispherical or dished (torispherical). More complicated shapes have historically been much harder to analyze for safe operation and are usually far tougher to construct.

Theoretically, a sphere would be the best shape of a pressure vessel. Unhappily, a spherical shape is tough to manufacture, therefore more expensive, so most pressure vessels are cylindrical with 2:1 semi-elliptical heads or end caps on each end. Smaller pressure vessels are assembled from a pipe and two covers. A disadvantage of these vessels is that greater breadths are more expensive, so that for example the most economic shape of a 1,000 litres (35 cu ft), 250 bars (3,600 psi) pressure vessel might be a breadth of 914.4 millimetres (36 in) and a width of 1,701.8 millimetres (67 in) including the 2:1 semi-elliptical domed end caps.

## Construction materials


Steel Pressure Vessel

Theoretically almost any material with good tensile properties that is chemically stable in the chosen application could be employed. However, pressure vessel design codes and application standards (ASME BPVC Section II, EN 13445-2 etc.) contain long lists of approved materials with associated limitations in temperature range.

Many pressure vessels are made of steel. To manufacture a cylindrical or spherical pressure vessel, rolled and possibly forged parts would have to be welded together. Some mechanical properties of steel, achieved by rolling or forging, could be adversely affected by welding, unless special precautions are taken. In addition to adequate mechanical strength, current standards dictate the use of steel with a high impact resistance, especially for vessels used in low temperatures. In applications where carbon steel would suffer corrosion, special corrosion resistant material should also be used.

Some pressure vessels are made of composite materials, such as filament wound composite using carbon fibre held in place with a polymer. Due to the very high tensile strength of carbon fibre these vessels can be very light, but are much more difficult to manufacture. The composite material may be wound around a metal liner, forming a composite overwrapped pressure vessel.

Other very common materials include polymers such as PET in carbonated beverage containers and copper in plumbing.

Pressure vessels may be lined with various metals, ceramics, or polymers to prevent leaking and protect the structure of the vessel from the contained medium. This liner may also carry a significant portion of the pressure load.

## Scaling

No matter what shape it takes, the minimum mass of a pressure vessel scales with the pressure and volume it contains and is inversely proportional to the strength to weight ratio of the construction material (minimum mass decreases as strength increases).

### Scaling of stress in walls of vessel

Pressure vessels are held together against the gas pressure due to tensile forces within the walls of the container. The normal (tensile) stress in the walls of the container is proportional to the pressure and radius of the vessel and inversely proportional to the thickness of the walls. Therefore pressure vessels are designed to have a thickness proportional to the radius of tank and the pressure of the tank and inversely proportional to the maximum allowed normal stress of the particular material used in the walls of the container.

Because (for a given pressure) the thickness of the walls scales with the radius of the tank, the mass of a tank (which scales as the length times radius times thickness of the wall for a cylindrical tank) scales with the volume of the gas held (which scales as length times radius squared). The exact formula varies with the tank shape but depends on the density, ρ, and maximum allowable stress σ of the material in addition to the pressure P and volume V of the vessel.

**Spherical vessel**

For a sphere, the mass of a pressure vessel is

$$M = \frac{3}{2} P V \frac{\rho}{\sigma},$$

where

*M* is mass,
*P* is the pressure difference from ambient (the gauge pressure),
*V* is volume,
ρ is the density of the pressure vessel material,
σ is the maximum working stress that material can tolerate.

Other shapes besides a sphere have constants larger than 3/2 (infinite cylinders take 2), although some tanks, such as non-spherical wound composite tanks can approach this.

**Cylindrical vessel with hemispherical ends**

This is sometimes called a "bullet" for its shape.

For a cylinder with hemispherical ends,

$$M = 2\pi R^2 (R + W) P \frac{\rho}{\sigma},$$

where

- R is the radius
- W is the middle cylinder width only, and the overall width is W + 2R

**2:1 Cylindrical vessel with semi-elliptical ends**

In a vessel with an aspect ratio of middle cylinder width to radius of 2:1,

$$M = 6\pi R^3 P \frac{\rho}{\sigma}.$$

**Gas storage**

In looking at the first equation, the factor PV, in SI units, is in units of (pressurization) energy. For a stored gas, PV is proportional to the mass of gas at a given temperature, thus

$$M = \frac{3}{2}nRT\frac{\rho}{\sigma}.$$

The other factors are constant for a given vessel shape and material. So we can see that there is no theoretical "efficiency of scale", in terms of the ratio of pressure vessel mass to pressurization energy, or of pressure vessel mass to stored gas mass. For storing gases, "tankage efficiency" is independent of pressure, at least for the same temperature.

So, for example, a typical design for a minimum mass tank to hold helium (as a pressurant gas) on a rocket would use a spherical chamber for a minimum shape constant, carbon fiber for best possible $\rho / \sigma$, and very cold helium for best possible $M / pV$.

## Stress in thin-walled pressure vessels

Stress in a shallow-walled pressure vessel in the shape of a sphere is

$$\sigma_\theta = \frac{pr}{2d},$$

where $\sigma_\theta$ is hoop stress, or stress in the circumferential direction, $p$ is internal gauge pressure, $r$ is the inner radius of the sphere, and $d$ is depth. A vessel can be considered "shallow-walled" if the diameter is at least 10 times (sometimes cited as 20 times) greater than the wall depth.

Stress in a shallow-walled pressure vessel in the shape of a cylinder is

$$\sigma_\theta = \frac{pr}{d},$$

$$\sigma_{\text{long}} = \frac{pr}{2d},$$

where $\sigma_\theta$ is hoop stress, or stress in the circumferential direction, $\sigma_{long}$ is stress in the longitudinal direction, $p$ is internal gauge pressure, $r$ is the inner radius of the cylinder, and $d$ is wall depth.

Almost all pressure vessel design standards contain variations of these two formulas with additional empirical terms to account for wall thickness, quality control of welds and in-service corrosion allowances.

### Winding angle of carbon fibre vessels

Wound infinite cylindrical shapes optimally take a winding angle of 54.7 degrees, as this gives the necessary twice the strength in the circumferential direction to the longitudinal.

## *Design and operation standards*

Pressure vessels are designed to operate safely at a specific pressure and temperature, technically referred to as the "Design Pressure" and "Design Temperature". A vessel that is inadequately designed to handle a high pressure constitutes a very significant safety hazard. Because of that, the design and certification of pressure vessels is governed by design codes such as the ASME Boiler and Pressure Vessel Code in North America, the Pressure Equipment Directive of the EU (PED), Japanese Industrial Standard (JIS), CSA B51 in Canada, AS1210 in Australia and other international standards like Lloyd's, Germanischer Lloyd, Det Norske Veritas, Société Générale de Surveillance (SGS S.A.), Stoomwezen etc.

Note that where the pressure-volume product is part of a safety standard, any incompressible liquid in the vessel can be excluded as it does not contribute to the potential energy stored in the vessel, so only the volume of the compressible part such as gas is used.

### List of standards

- EN 13445: The current European Standard, harmonized with the Pressure Equipment Directive (97/23/EC). Extensively used in Europe.
- ASME Code Section VIII, in addition supported by Sections II (materials), V (NDT/NDE) and IX (welding). Published by the American Society of Mechanical Engineers.
  - ASME Code Section VIII Division 1: US standard, design by formula. Almost exclusively used in North America, widely used worldwide.
  - ASME Code Section VIII Division 2: Alternative Rules, design by analysis.
  - ASME Code Section VIII Division 3: Alternative Rules for Construction of High Pressure Vessel
- BS 5500: Former British Standard, replaced in the UK by EN 13445 but retained under the name PD 5500 for the design and construction of export equipment.
- AD Merkblätter: German standard, harmonized with the Pressure Equipment Directive.
- EN 286 (Parts 1 to 4): European standard for simple pressure vessels (air tanks), harmonized with Council Directive 87/404/EEC.
- BS 4994: Specification for design and construction of vessels and tanks in reinforced plastics.
- ASME PVHO: US standard for Pressure Vessels for Human Occupancy
- CODAP
- AS 1210

- API 510
- ISO 11439
- IS 2825-1969 (RE1977)_code_unfired_Pressure_vessels
- FRP tanks and vessels
- AIAA S-080-1998: AIAA Standard for Space Systems - Metallic Pressure Vessels, Pressurized Structures, and Pressure Components
- AIAA S-081A-2006: AIAA Standard for Space Systems - Composite Overwrapped Pressure Vessels (COPVs)
- B51-09 Canadian Boiler, pressure vessel, and pressure piping code
- Stoomwezen: Former pressure vessels code in the Netherlands

### Leak Before Burst

Leak before burst describes a pressure vessel designed such that a crack in the vessel will grow through the wall, allowing the contained fluid to escape and reducing the pressure, prior to growing so large as to cause fracture at the operating pressure.

Many pressure vessel standards, including the ASME Boiler and Pressure Vessel Code and the AIAA metallic pressure vessel standard, either require pressure vessel designs to be leak before burst, or require pressure vessels to meet more stringent requirements for fatigue and fracture if they are not shown to be leak before burst.

## *Alternatives to pressure vessels*

Depending on the application and local circumstances, alternatives to pressure vessels exist. Examples can be seen in domestic water collection systems, where the following may be used:

- Gravity controlled systems which typically consist of an unpressurized water tank at an elevation higher than the point of use. Pressure at the point of use is the result of the hydrostatic pressure caused by the elevation difference. Gravity systems produce 0.43 pounds per square inch (3.0 kPa) per foot of water head (elevation difference). A municipal water supply or pumped water is typically around 90 pounds per square inch (620 kPa).
- Inline pump controllers or pressure-sensitive pumps.

## *History of pressure vessels*


A 10,000 psi (69 MPa) pressure vessel from 1919, wrapped with high tensile steel banding and steel rods to secure the end caps.

Large pressure vessels were invented during the industrial revolution, particularly in Great Britain, to be used as boilers for making steam to drive steam engines.

Design and testing standards and a system of certification came about as the result of fatal boiler explosions.

In an early effort to design a tank capable of withstanding pressures up to 10,000 psi (69 MPa), a 6-inch (150 mm) diameter tank was developed in 1919 that was spirally-wound with two layers of high tensile strength steel wire to prevent sidewall rupture, and the end caps longitudinally reinforced with lengthwise high-tensile rods.

# Chapter 7

# Valve

These water valves are operated by handles.

A **valve** is a device that regulates the flow of a fluid (gases, liquids, fluidized solids, or slurries) by opening, closing, or partially obstructing various passageways. Valves are technically pipe fittings, but are usually discussed as a separate category. In an open valve, fluid flows in a direction from higher pressure to lower pressure.

Valves are also found in the human body. For example, there are several heart valves which control the flow of blood in the chambers of the heart and maintain the correct pumping action.

Valves are used in a variety of contexts, including industrial, military, commercial, residential, and transport.

The industries in which the majority of valves are used are oil and gas, power generation, mining, water reticulation, sewerage and chemical manufacturing.

Plumbing valves, such as taps for hot and cold tap water are the most noticeable types of valves. Other valves encountered on a daily basis include gas control valves on cookers, small valves fitted to washing machines and dishwashers, and safety devices fitted to hot water systems.

Valves may be operated manually, either by a handle, lever or pedal. Valves may also be automatic, driven by changes in pressure, temperature, or flow. These changes may act upon a diaphragm or a piston which in turn activates the valve, examples of this type of valve found commonly are safety valves fitted to hot water systems or boilers.

More complex control systems using valves requiring automatic control based on an external input (i.e., regulating flow through a pipe to a changing set point) require an actuator. An actuator will stroke the valve depending on its input and set-up, allowing the valve to be positioned accurately, and allowing control over a variety of requirements.

Valves are also found in the Otto cycle (internal combustion) engines driven by a camshaft, tappets or push rods where they play a major role in engine cycle control.

## *Applications*

Valves vary widely in form and application. Sizes typically range from 0.1 mm 60 cm (2 ft). Special valves can have a diameter exceeding 5 meters.

Valve cost ranges from simple inexpensive disposable valves to specialized valves cost thousands of US dollars per inch of diameter.

Disposable valves may be found inside common household items including mini-pump dispensers and aerosol cans.

### *Types*

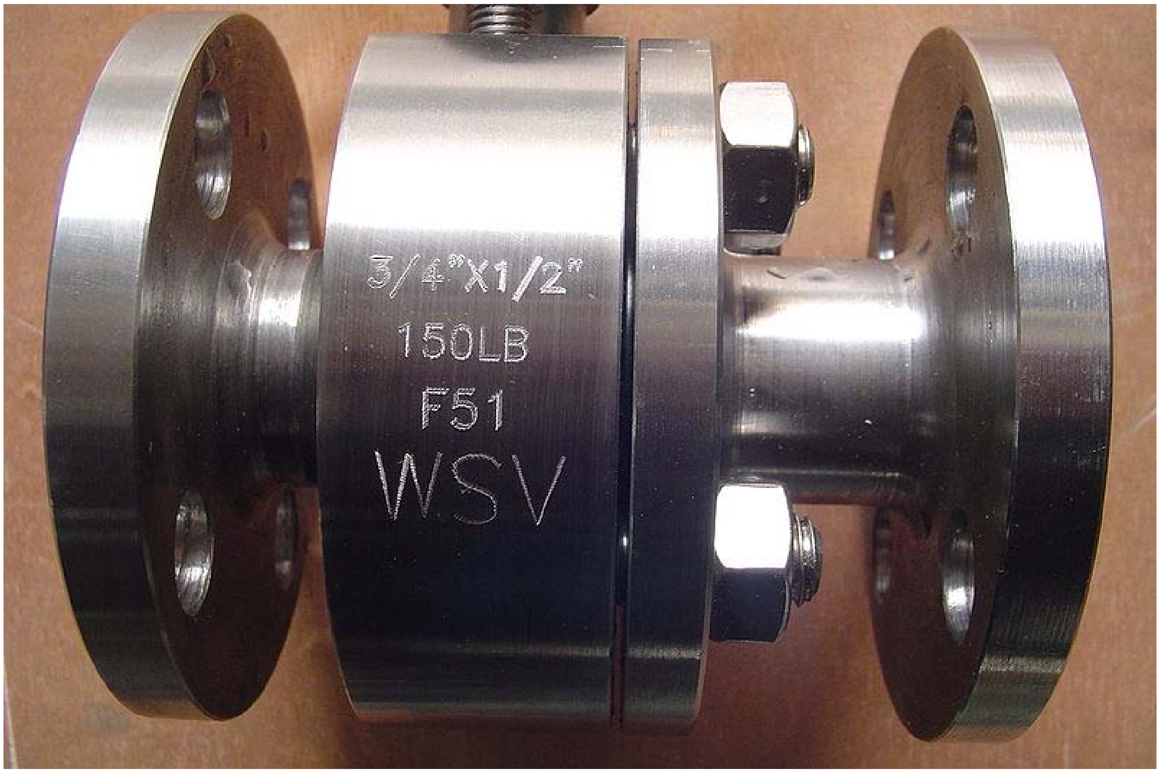
The inside of an extremely large butterfly valve

Valves are quite diverse and may be classified into a number of basic types. Valves may also be classified by how they are actuated:

- Hydraulic
- Pneumatic
- Manual
- Solenoid
- Motor

### Basic types

Valves can be categorized into the following basic types:




Duplex ball valve

- Ball valve, for on/off control without pressure drop, and ideal for quick shut-off since a 90º turn offers complete shut-off angle, compared to multiple turns required on most manual valves.
- Butterfly valve, for flow regulation in large pipe diameters.
- Ceramic Disc valve, used mainly in high duty cycle applications or on abrasive fluids. Ceramic disc can also provide Class IV seat leakage
- Check valve or non-return valve, allows the fluid to pass in one direction only.


Hastelloy check valve

- Choke valve, a valve that raises or lowers a solid cylinder which is placed around or inside another cylinder which has holes or slots. Used for high pressure drops found in oil and gas wellheads.
- Diaphragm valve, some are sanitary predominantly used in the pharmaceutical and food-industry.
- Gate valve, mainly for on/off control, with low pressure drop.


Stainless steel gate valve

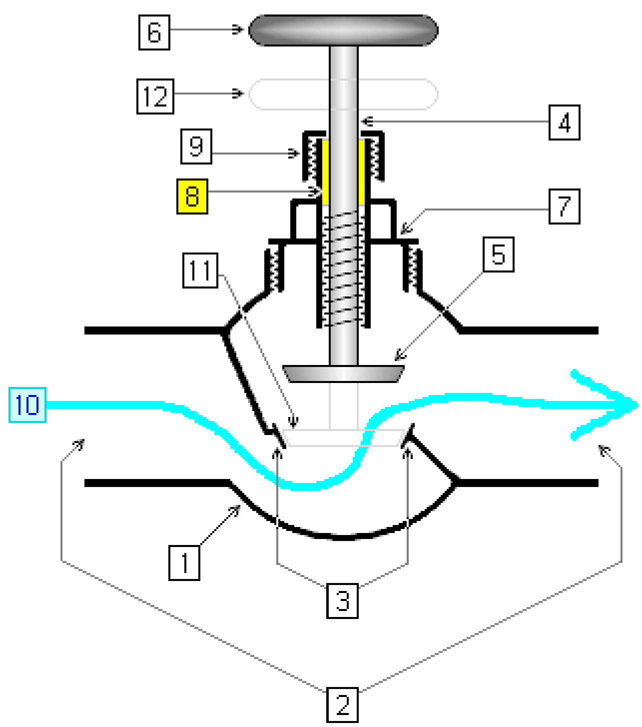
- Globe valve, good for regulating flow.
- Knife valve, for slurries or powders on/off control.
- Needle valve for accurate flow control.
- Pinch valve, for slurry flow regulation.
- Piston valve, for regulating fluids that carry solids in suspension.
- Plug valve, slim valve for on/off control but with some pressure drop.
- Poppet valve
- Spool valve, for hydraulic control
- Thermal expansion valve, used in refrigeration and air conditioning systems.

## Specific types

- Aspin valve: a cone-shaped metal part fitted to the cylinder head of an engine
- Ball cock: often used as a water level controller (cistern)
- Bibcock: provides a connection to a flexible hosepipe
- Blast valve: prevents rapid overpressures in a fallout shelter or a bunker
- Cock: colloquial term for a small valve or a stopcock
- Demand valve: on a diving regulator
- Double beat valve
- Double check valve
- Duckbill valve
- Flipper valve
- Flow control valve: an application which maintains a variable flow rate through the valve
- Heimlich valve: a specific one-way valve used on the end of chest drain tubes to treat a pneumothorax
- Foot valve: a check valve on the foot of a suction line to prevent backflow
- Four-way valve: was used to control the flow of steam to the cylinder of early double-acting steam engines
- Freeze seal/Freeze plug: in which freezing and melting the fluid creates and removes a plug of frozen material acting as the valve
- Gas pressure regulator regulates the flow and pressure of a gas
- Heart valve: regulates blood flow through the heart in many organisms
- Leaf valve: one-way valve consisting of a diagonal obstruction with an opening covered by a hinged flap
- Pilot valve: regulate flow or pressure to other valves
- Poppet valve and sleeve valve: commonly used in piston engines to regulate the fuel mixture intake and exhaust
- Pressure regulator or pressure reducing valve (PRV): reduces pressure to a preset level downstream of the valve
- Pressure sustaining valve, or back-pressure regulator: maintains pressure at a preset level upstream of the valve
- Presta and Schrader valves are used to hold the air in bicycle tires
- Reed valve: consists of two or more flexible materials pressed together along much of their length, but with the influx area open to allow one-way flow, much like a heart valve
- Regulator: used in SCUBA diving equipment and in gas cooking equipment to reduce the high pressure gas supply to a lower working pressure
- Rocker valve
- Rotary valves and piston valves: parts of brass instruments used to change their pitch
- Rupture disc: a one time use replaceable valve for rapid pressure relief, used to protect piping systems from excessive pressure or vacuum; more reliable than a safety valve
- Saddle valve: where allowed, is used to tap a pipe for a low-flow need

- Safety valve or relief valve: operates automatically at a set differential pressure to correct a potentially dangerous situation, typically over-pressure
- Schrader valve: used to hold the air inside automobile tires
- Solenoid valve: an electrically controlled hydraulic or pneumatic valve
- Stopcock: restricts or isolates flow through a pipe
- Swirl valve: A specially designed Joule-Thompson pressure reduction/expansion valve imparting a centrifugal force upon the discharge stream for improving gas-liquid phase separation
- Tap (British English), faucet (American English): the common name for a valve used in homes to regulate water flow
- Thermal expansion valve, used in air conditioning and refrigeration systems.
- Thermostatic Mixing Valve
- Thermostatic Radiator Valve
- Trap primer: sometimes include other types of valves, or are valves themselves
- Vacuum breaker valve: prevents the back-siphonage of contaminated water into pressurized drinkable water supplies

## *Components*




Cross-sectional diagram of an open globe **valve**.
1. **body**
2. **ports**
3. **seat**
4. **stem**
5. **disc** when valve is open

6. **handle** or **handwheel** when valve is open
7. **bonnet**
8. **packing**
9. **gland nut**
10. **fluid flow** when valve is open
11. position of disc if valve were shut
12. position of handle or handwheel if valve were shut

The main parts of a valve are the **body** and the **bonnet**. These two parts form the casing that holds the fluid going through the valve.

## Body

The valve's **body** is the outer casing of most or all of the valve that contains the internal parts or *trim*. The bonnet is the part of the encasing through which the stem (see below) passes and that forms a guide and seal for the stem. The bonnet typically screws into or is bolted to the valve body.

Valve bodies are usually metallic or plastic. Brass, bronze, gunmetal, cast iron, steel, alloy steels and stainless steels are very common. Seawater applications, like desalination plants, often use duplex valves, as well as super duplex valves, due to their corrosion resistant properties, particularly against warm seawater. Alloy 20 valves are typically used in sulphuric acid plants, whilst monel valves are used in hydrofluoric acid (HF Acid) plants. Hastelloy valves are often used in high temperature applications, such as nuclear plants, whilst inconel valves are often used in hydrogen applications. Plastic bodies are used for relatively low pressures and temperatures. PVC, PP, PVDF and glass-reinforced nylon are common plastics used for valve bodies.

## Bonnet

A **bonnet** acts as a cover on the valve body. It is commonly semi-permanently screwed into the valve body or bolted onto it. During manufacture of the valve, the internal parts are put into the body and then the bonnet is attached to hold everything together inside. To access internal parts of a valve, a user would take off the bonnet, usually for maintenance. Many valves do not have bonnets; for example, plug valves usually do not have bonnets. Many ball valves do not have bonnets since the valve body is put together in a different style, such as being screwed together at the middle of the valve body.

## Ports

**Ports** are passages that allow fluid to pass through the valve. Ports are obstructed by the **valve member** or **disc** to control flow. Valves most commonly have 2 ports, but may have as many as 20. The valve is almost always connected at its ports to pipes or other components. Connection methods include threadings, compression fittings, glue, cement, flanges, or welding.

## Handle or actuator

A **handle** is used to manually control a valve from outside the valve body. Automatically controlled valves often do not have handles, but some may have a handle (or something similar) anyway to manually override automatic control, such as a stop-check valve. An **actuator** is a mechanism or device to automatically or remotely control a valve from outside the body. Some valves have neither handle nor actuator because they automatically control themselves from inside; for example, check valves and relief valves may have neither.

## Disc

Valve disc

A **disc** or **valve member** is a movable obstruction inside the stationary body that adjustably restricts flow through the valve. Although traditionally disc-shaped, discs come in various shapes. Depending on the type of valve, a disc can move linearly inside a valve, or rotate on the stem (as in a butterfly valve), or rotate on a hinge or trunnion (as in a check valve). A *ball* is a round valve member with one or more paths between ports passing through it. By rotating the ball, flow can be directed between different ports. Ball valves use spherical rotors with a cylindrical hole drilled as a fluid passage. Plug valves use cylindrical or conically tapered rotors called **plugs**. Other round shapes for rotors are possible as well in **rotor valves**, as long as the rotor can be turned inside the valve body.

However not all round or spherical discs are rotors; for example, a ball check valve uses the ball to block reverse flow, but is not a rotor because operating the valve does not involve rotation of the ball.

## Seat

The **seat** is the interior surface of the body which contacts the disc to form a leak-tight seal. In discs that move linearly or swing on a hinge or trunnion, the disc comes into contact with the seat only when the valve is shut. In disks that rotate, the seat is always in contact with the disk, but the area of contact changes as the disc is turned. The seat always remains stationary relative to the body.

Seats are classified by whether they are cut directly into the body, or if they are made of a different material:

- **Hard seats** are integral to the valve body. Nearly all hard seated metal valves have a small amount of leakage.
- **Soft seats** are fitted to the valve body and made of softer materials such as PTFE or various elastomers such as NBR, EPDM, or FKM depending on the maximum operating temperature.

The shut off butterfly valve for a Francis turbine at Gordon Power Station, Tasmania

Ball valve

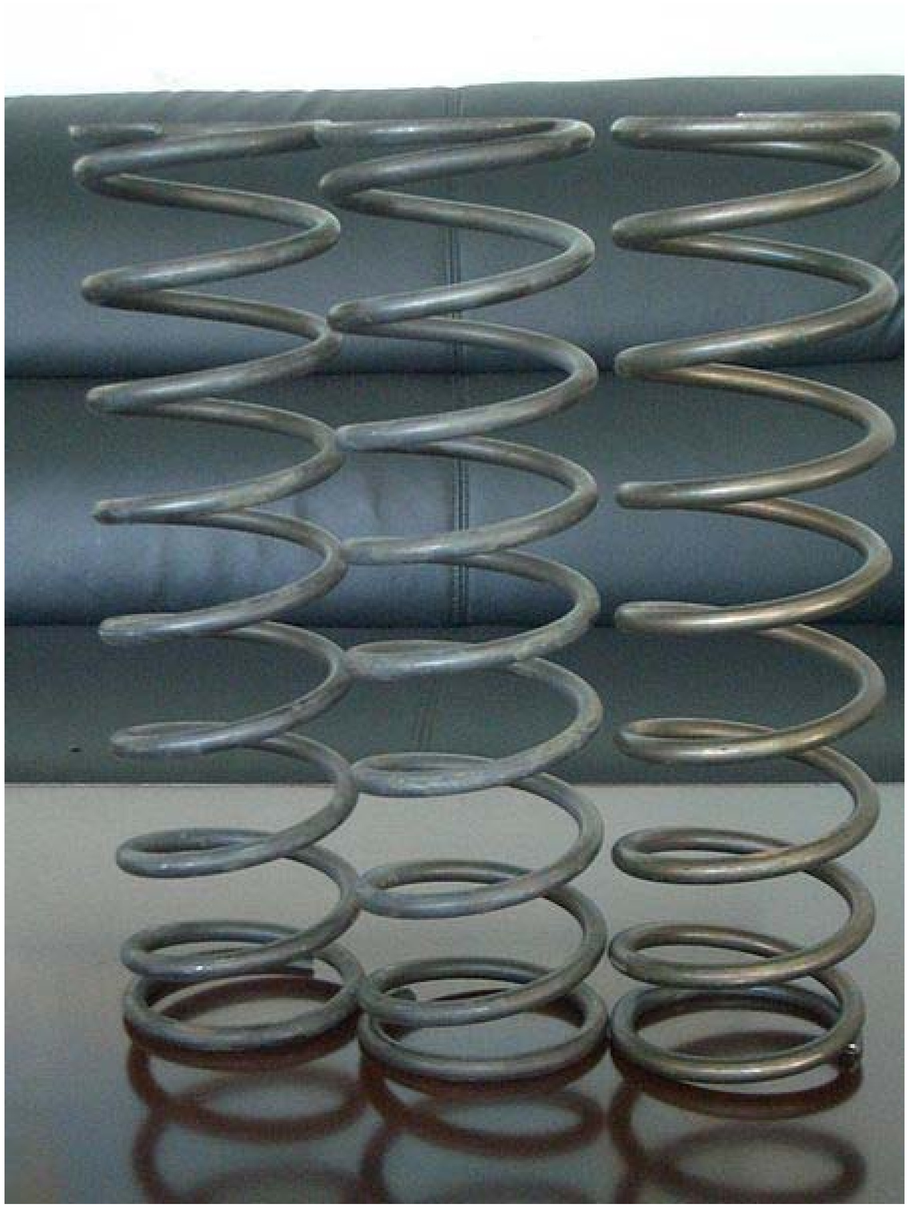
A closed soft seated valve is much less liable to leak when shut while hard seated valves are more durable. Gate, globe, and check valves are usually hard seated while butterfly, ball, plug, and diaphragm valves are usually soft seated.

## Stem

The **stem** transmits motion from the handle or controlling device to the disc. The stem typically passes through the bonnet when present. In some cases, the stem and the disc can be combined in one piece, or the stem and the handle are combined in one piece.

The motion transmitted by the stem may be a linear force, a rotational torque, or some combination of these(Angle valve using torque reactor pin and Hub Assembly). The valve and stem can be threaded such that the stem can be screwed into or out of the valve by turning it in one direction or the other, thus moving the disc back or forth inside the body. Packing is often used between the stem and the bonnet to maintain a seal. Some valves have no external control and do not need a stem as in most check valves.

Valves whose disc is between the seat and the stem and where the stem moves in a direction into the valve to shut it are **normally-seated** or **front seated**. Valves whose seat is between the disc and the stem and where the stem moves in a direction out of the valve to shut it are **reverse-seated** or **back seated**. These terms don't apply to valves with no stem or valves using rotors.



Inconel X750 Spring

## Gaskets

The seals or packings used to prevent the escape of a gas or fluids from valves.

## Valve balls

A valve ball is also used for severe duty, high-pressure, high-tolerance applications. They are typically made of stainless steel, titanium, Stellite, Hastelloy, brass, or nickel. They can also be made of different types of plastic, such as ABS, PVC, PP or PVDF.

## Spring

Many valves have a spring for spring-loading, to normally shift the disc into some position by default but allow control to reposition the disc. Relief valves commonly use a spring to keep the valve shut, but allow excessive pressure to force the valve open against the spring-loading. Coil springs are normally used. Typical spring materials include zinc plated steel, stainless steel, and for high temperature applications Inconel X750.

## Trim

The internal elements of a valve are collectively referred to as a valve's **trim**. According to API Standards 600, "Steel Gate Valve-Flanged and Butt-welding Ends, Bolted Bonnets", the trim consists of stem, seating surface in the body, gate seating surface, bushing or a deposited weld for the backseat and stem hole guide, and small internal parts that normally contact the service fluid, excluding the pin that is used to make a stem-to-gate connection (this pin shall be made of an austenitic stainless steel material).

### *Valve operating positions*

A seacock for cooling seawater, on a marine diesel engine.

Valve **positions** are operating conditions determined by the position of the disc or rotor in the valve. Some valves are made to be operated in a gradual change between two or more positions. Return valves and non-return valves allow fluid to move in 2 or 1 directions respectively.

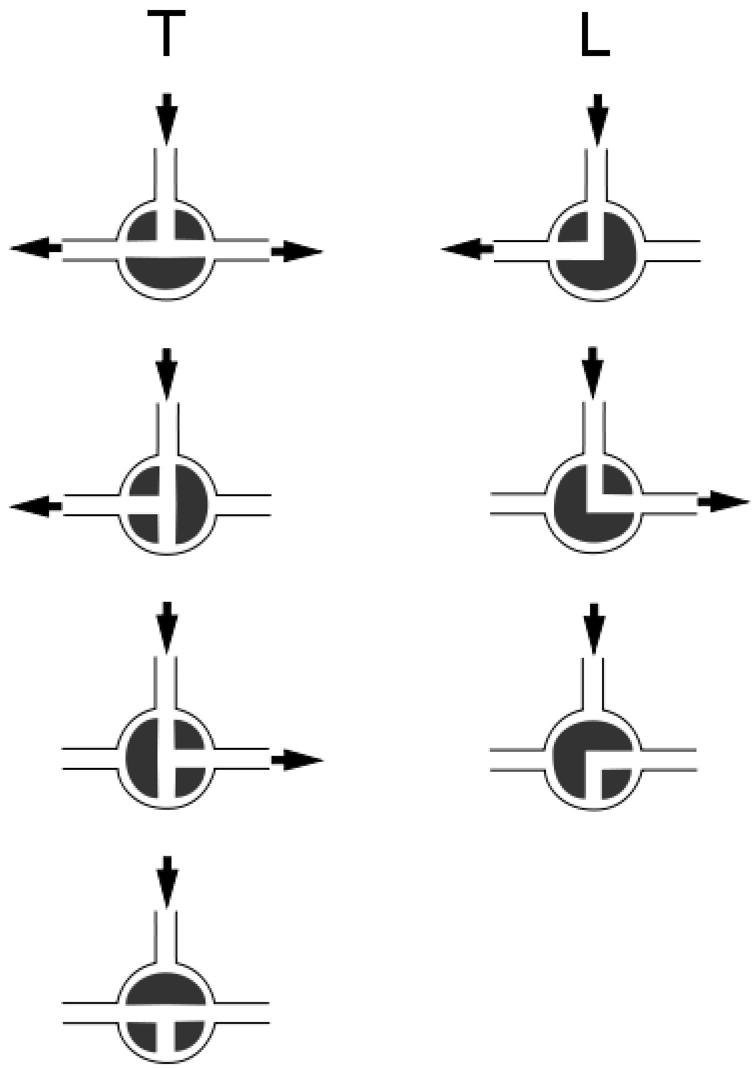
### Two-port valves

Operating positions for 2-port valves can be either shut (closed) so that no flow at all goes through, fully open for maximum flow, or sometimes partially open to any degree in between. Many valves are not designed to precisely control intermediate degree of flow; such valves are considered to be either open or shut. Some valves are specially designed to regulate varying amounts of flow. Such valves have been called by various names such as *regulating*, *throttling*, *metering*, or *needle valves*. For example, needle valves have elongated conically-tapered discs and matching seats for fine flow control. For some valves, there may be a mechanism to indicate by how much the valve is open, but in many cases other indications of flow rate are used, such as separate flow meters.

In plants with remote-controlled process operation, such as oil refineries and petrochemical plants, some 2-way valves can be designated as normally closed (NC) or normally open (NO) during regular operation. Examples of normally closed valves are *sampling valves*, which are only opened while a sample is taken. Examples of normally open valves are *isolation valves*, which are usually only shut when there is a problem with a unit or a section of a fluid system such as a leak in order to isolate the problem from the rest of the system.

Although many 2-way valves are made in which the flow can go in either direction between the two ports, when a valve is placed into a certain application, flow is often expected to go from one certain port on the **upstream** side of the valve, to the other port on the **downstream** side. Pressure regulators are variations of valves in which flow is controlled to produce a certain downstream pressure, if possible. They are often used to control flow of gas from a gas cylinder. A back-pressure regulator is a variation of a valve in which flow is controlled to maintain a certain upstream pressure, if possible.

### Three-port valves




Schematic 3 way ball valve: L-shaped ball right, T-shaped left

Valves with three ports serve many different functions. A few of the possibilities are listed here.

*Three-way ball valves* come with a T- or L- shaped fluid passageways inside the rotor. The T valve might be used to permit connection of one inlet to either or both outlets or connection of the two outlets. The L valve could be used to permit disconnection of both or connection of either but not both of two inlets to one outlet.

*Shuttle valves* automatically connect the higher pressure inlet to the outlet while (in some configurations) preventing flow from one inlet to the other.

*Single handle mixer valves* produce a variable mixture of hot and cold water at a variable flow rate under control of a single handle.

*Thermostatic mixing valves* mix hot and cold water to produce a constant temperature in the presence of variable pressures and temperatures on the two input ports.

### Four-port valves

A 4-port valve is a valve whose body has four ports equally spaced round the body and the disc has two passages to connect adjacent ports. It is operated with two positions.

It can be used to isolate and to simultaneously bypass a sampling cylinder installed on a pressurized water line. It is useful to take a fluid sample without affecting the pressure of a hydraulic system and to avoid degassing (no leak, no gas loss or air entry, no external contamination)....

## *Control*


A sailor aboard a ship operates the wheel controlling a fuel valve.

Many valves are controlled manually with a handle attached to the stem. If the handle is turned ninety degrees between operating positions, the valve is called a **quarter-turn valve**. Butterfly, ball valves, and plug valves are often quarter-turn valves. If the handle is circular with the stem as the axis of rotation in the center of the circle, then the handle is called a **handwheel**. Valves can also be controlled by actuators attached to the stem.

They can be electromechanical actuators such as an electric motor or solenoid, pneumatic actuators which are controlled by air pressure, or hydraulic actuators which are controlled by the pressure of a liquid such as oil or water. Actuators can be used for the purposes of automatic control such as in washing machine cycles, remote control such as the use of a centralised control room, or because manual control is too difficult such as when the valve is very large. Pneumatic actuators and hydraulic actuators need pressurised air or liquid lines to supply the actuator: an inlet line and an outlet line. Pilot valves are valves which are used to control other valves. Pilot valves in the actuator lines control the supply of air or liquid going to the actuators.

The fill valve in a toilet water tank is a liquid level-actuated valve. When a high water level is reached, a mechanism shuts the valve which fills the tank.

In some valve designs, the pressure of the flow fluid itself or pressure difference of the flow fluid between the ports automatically controls flow through the valve.

## *Other considerations*

Valves are typically rated for maximum temperature and pressure by the manufacturer. The wetted materials in a valve are usually identified also. Some valves rated at very high pressures are available. When a designer, engineer, or user decides to use a valve for an application, he/she should ensure the rated maximum temperature and pressure are never exceeded and that the wetted materials are compatible with the fluid the valve interior is exposed to. In Europe, valve design and pressure ratings are subject to statutory regulation under the Pressure Equipment Directive 97/23/EC (PED)

Some fluid system designs, especially in chemical or power plants, are schematically represented in piping and instrumentation diagrams. In such diagrams, different types of valves are represented by certain symbols.

Valves in good condition should be leak-free. However, valves may eventually wear out from use and develop a leak, either between the inside and outside of the valve or, when the valve is shut to stop flow, between the disc and the seat. A particle trapped between the seat and disc could also cause such leakage.

Globe valve


A valve controlled by a wheel

Large butterfly valve

Cast iron butterfly valve

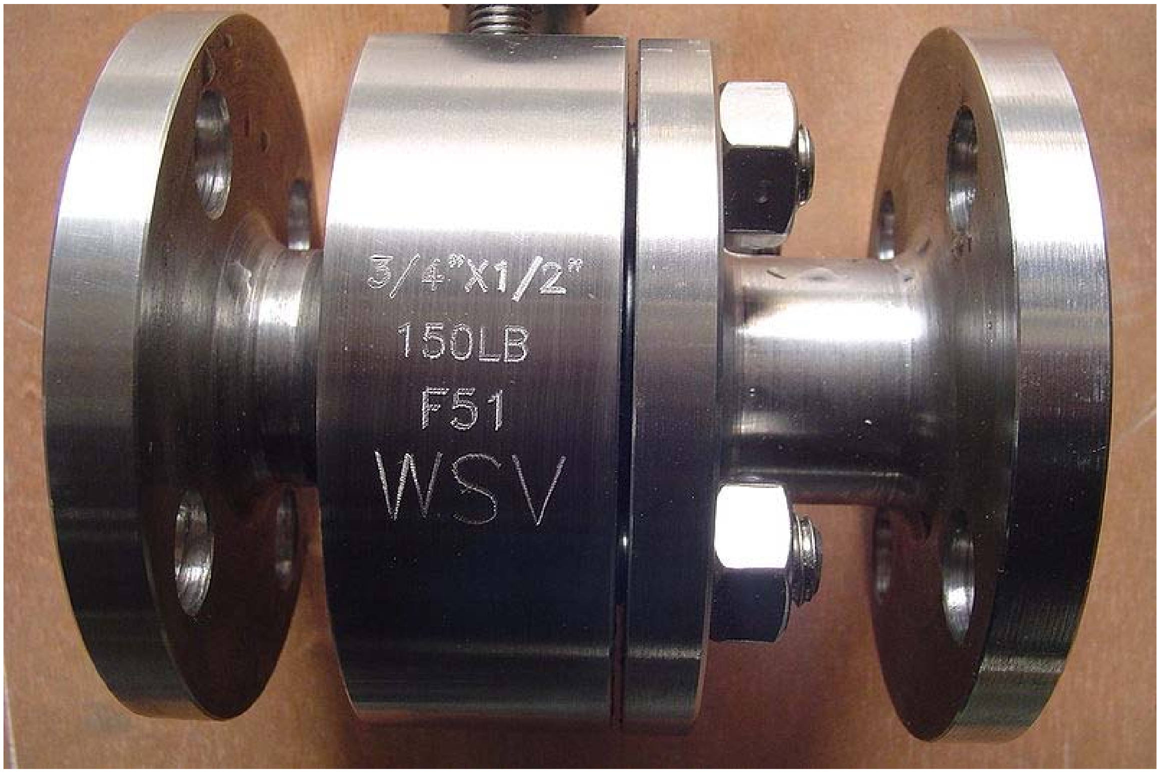
Cast iron butterfly valve


Hastelloy ball valve


Stainless steel gate valve


Stainless steel gate valve

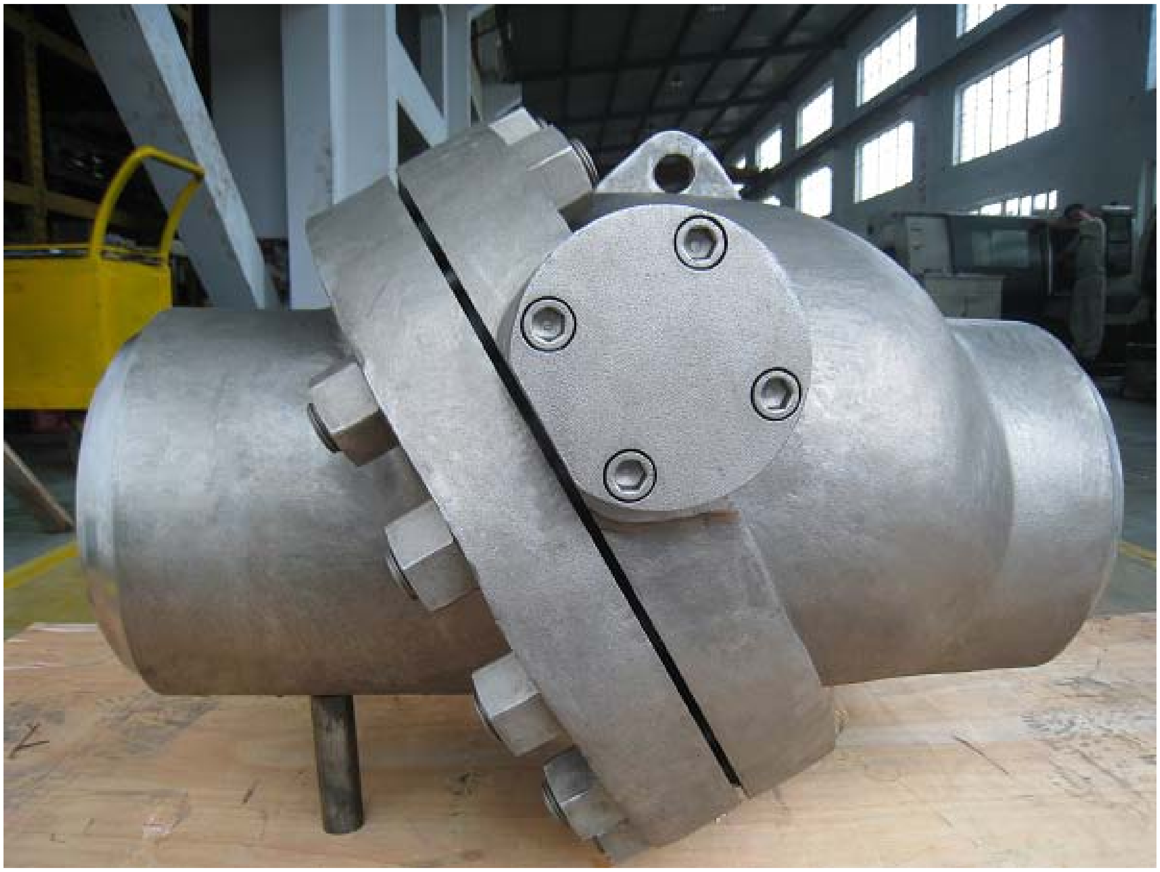

Hastelloy check valves




Duplex ball valve


Inconel gate valve


Stainless steel wafer check valve



Inconel check valve

Stainless steel ball valve


Cryogenic 254 SMO gate valve


Inside view of a tilting disc inconel check valve

Duplex ball valves

Cryogenic super duplex gate valve frozen up during operation

Super duplex ball valves


Flanged nozzle inconel check valve or axial check valve

Inside hastelloy check valve, wafer configuration

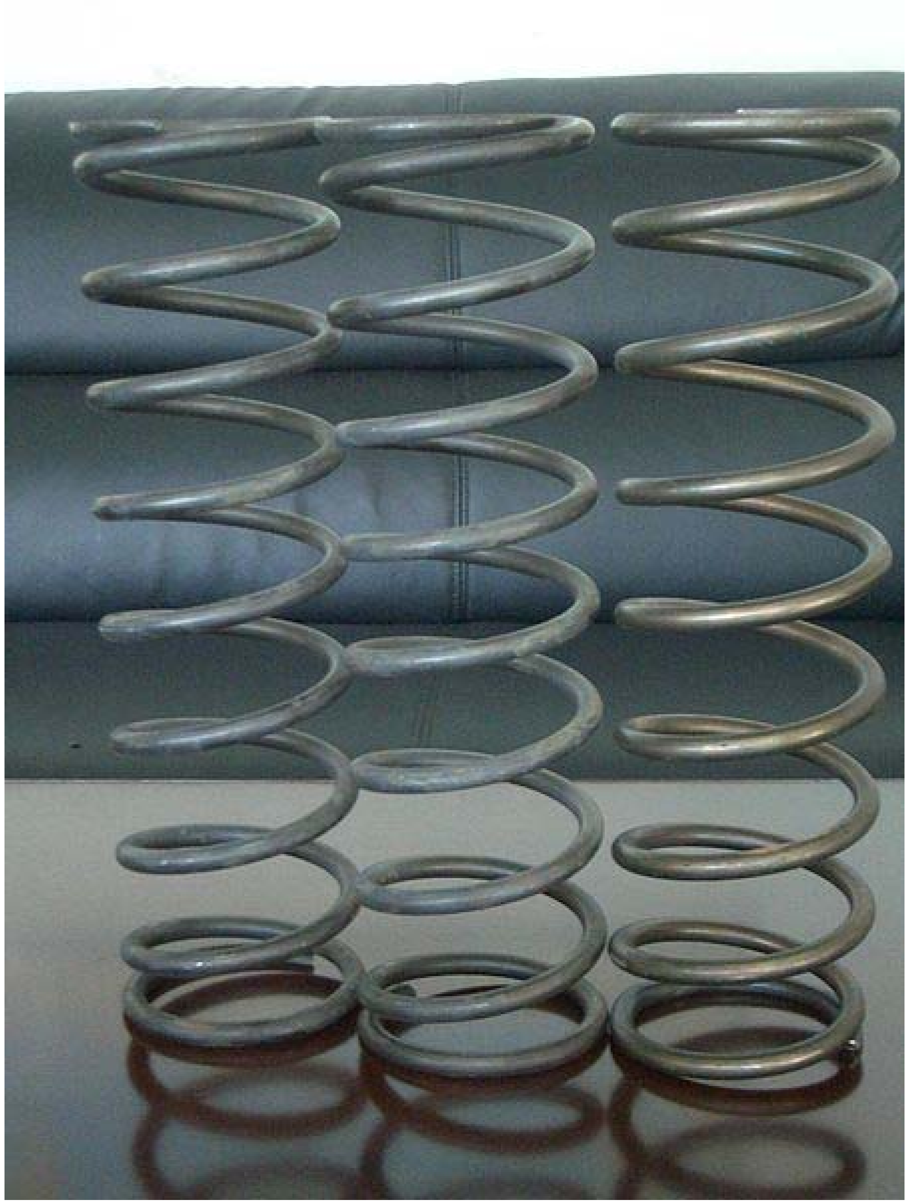
Large carbon steel swing check valve

Disc for an alloy check valve also known as axial check valve

Balls for alloy ball valves

Wafer check valve

Nuts and bolts for incoloy valves



Inconel check valve springs

Ball for a titanium ball valve

## Chapter 8

# Gas Cylinder


Industrial compressed gas cylinders used for oxy-fuel welding and cutting of steel.

A **gas cylinder** or tank is a pressure vessel used to store gases at above atmospheric pressure. High pressure gas cylinders are also called bottled gases.

## *Nomenclature differences*

In the United States, 'bottled gas' typically refers to liquefied petroleum gas. 'Bottled gas' is sometimes used in medical supply, especially for portable oxygen tanks. Packaged industrial gases are frequently called 'cylinder gas', though 'bottled gas' is sometimes used.

The United Kingdom and other parts of Europe more commonly refer to 'bottled gas' when discussing any usage whether industrial, medical or liquefied petroleum. However, in contrast, what the United States calls liquefied petroleum gas is known generically in the United Kingdom as 'LPG'; and it may be ordered using by one of several Trade names, or specifically as butane or propane depending on the required heat output.

## *Regulations and testing*

The transportation of high pressure cylinders is regulated by many governments throughout the world. Various levels of testing are generally required by the governing authority for the country in which it is to be transported. In the United States, this authority is the United States Department of Transportation (DOT). For Canada, this authority is Transport Canada (TC). Cylinders may have additional requirements placed on design and or performance from independent testing agencies such as Underwriter's Laboratory (UL). Each manufacturer of high pressure cylinders is required to have independent quality agent that will inspect the product for quality and safety.

There are a variety of tests that may be performed on various cylinders. Some of the most common types of tests are hydrostatic test, burst test, tensile strength, Charpy impact test and pressure cycling.

During the manufacturing process, vital information is usually stamped or permanently marked on the cylinder. This information usually includes the type of cylinder, the working or service pressure, the serial number, date of manufacture, the manufacture's registered code and sometimes the test pressure. Other information may also be stamped depending on the regulation requirements.

High pressure cylinders that are used multiple times—as most are—can be hydrostatically or ultrasonically tested and visually examined every few years. In the U.S., hydrostatic/ultrasonic testing is required either every five years or every ten years, depending on cylinder and its service. Helium Gas tanks have the highest pressures possible when full, around 1000 atmospheres.

## *Valve connections*


A gas regulator attached to a nitrogen cylinder. From right - main valve, tank pressure gauge, low-pressure valve, outlet pressure gauge, 3-way outlet terminated by needle valves.

When gases are supplied in gas cylinders, the cylinders have a stop angle valve at the end on top. Often, gas cylinders are somewhat long and narrow and may stand upright on a flattened bottom at one end with the valve at the top. During storage, transportation, and handling when the gas is not in use, a cap may be screwed over the protruding valve to protect it from damage or breaking off in case the cylinder were to fall over. Instead of a cap, cylinders commonly have a protective collar or neck ring around the service valve assembly.

When the gas in the cylinder is ready to be used, the cap is taken off and a pressure-regulating assembly is attached to the stop valve. This attachment typically has a pressure regulator with upstream (inlet) and downstream (outlet) pressure gauges and a further downstream needle valve and outlet connection. For gases that remain gaseous under ambient storage conditions, the upstream pressure gauge can be used to estimate how much gas is left in the cylinder according to pressure. For gases that are liquid under storage (e.g. propane), the outlet pressure is dependent on the vapor pressure of the gas, and does not fall until the cylinder is nearly exhausted. The regulator could be adjusted to control the flow of gas out of the cylinder according to pressure shown by the downstream gauge. The outlet connection is attached to whatever needs the gas supply, such as a balloon for example.

The valves on industrial, medical and diving cylinders are usually of different size and type, as are the valves for different products, making it more difficult to mistakenly misuse a gas.

In the US, valve connections are sometimes referred to as 'CGA connections,' since the Compressed Gas Association (CGA) publishes guidelines on what connections to use for what products (e.g., In the USA, an argon cylinder will have a CGA 580 connection on the valve).

- Note: if the nut on a CGA connection has a notch in it, it uses a left-handed thread.

High purity gases will sometimes use CGA-DISS ('Diameter Index Safety System') connections.

In the EU, DIN connections are more common than in the US.

### *Color coding*

Gas cylinders are often color coded, but the codes are not standard across different jurisdictions, and sometimes are not regulated. Cylinder color can not safely be used for positive product identification; cylinders have labels which identify the gas they contain and the label alone should be used for positive identification.

### *Safety and standards*

**Good** Handling: **Gas cylinders** chained to a wall for safety at Duke University. Note the protective caps covering the valves at top of each cylinder.


**Bad** Handling: A **gas cylinder** in an Indian Auto rickshaw with the valve sticking out without protective cap.

Because the contents are under pressure and are sometimes hazardous, there are special safety regulations for handling bottled gases. These include chaining bottles to prevent falling and breaking, proper ventilation to prevent injury or death in case of leaks and signage to indicate the potential hazards. Installing and replacing gas cylinders should be done by trained personnel.

In a fire, the pressure in a gas cylinder rises in direct proportion to its temperature. If the internal pressure exceeds the mechanical limitations of the cylinder and there are no means to safely vent the pressurized gas to the atmosphere, the vessel will fail mechanically. If the vessel contents are ignitable, this event may result in a "fireball". If the cylinder's contents are liquid but become a gas at ambient conditions, this is commonly referred to as a Boiling Liquid Expanding Vapour Explosion (BLEVE).

Medical gas cylinders in the UK and other countries have a seal of Wood's metal between the valve block and the cylinder body. This seal melts at a comparatively low temperature

(70°C) and allows the contents of the cylinder to escape in a controlled fashion, lessening the risk of explosion.

More common pressure relief devices are of a simple burst disc type. In these, a small burst disc is installed in the back of the valve. A burst disc is a small metal gasket engineered to rupture at a pre-determined pressure. Some of these burst disc are backed with a low-melting-point metal, so that the valve must be exposed to excessive heat before the burst disc can rupture.

The Compressed Gas Association sells a number of booklets and pamphlets on safe handling and use of bottled gases.

If the valve of a compressed air cylinder is broken or sheared off, the released pressure may cause the cylinder to act like a rocket, shooting away quickly.

### Standards

- ISO 11439: Gas cylinders—High pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles
- ISO 15500-5: Road vehicles -- Compressed natural gas (CNG) fuel system components -- Part 5: Manual cylinder valve

## *Management*

Carelessness with pressurized gas cylinders can have devastating consequences including serious injuries or death, property and environmental damage.

Cylinders should be properly labeled and securely stored. Substances that may react with each other (e.g., oxidizers and flammable materials) should not be stored in close proximity.

## *Sizes*

In scuba diving, the USA measures cylinder volume by the amount of free air that can be compressed into the cylinder; Europe measures the cylinder volume as the internal volume of the cylinder: e.g. USA 19 cubic feet = European 3 liter at 180 bar.

The below are example cylinder sizes and do not constitute an industry standard.

| Cyl. Size | Size* Diameter X Height (inches) Includes 5.5 inches for valve and cap. | Nominal* Tare Weight (lbs.) Includes 4.5 lbs. for valve and cap. | Water Capacity (lbs.) | Internal Volume @ 70°F (21°C), 1 ATM (liters/cubic feet) | US DOT Specs |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| T | 9.25 X 60 | 135 | 110 | 49.9 / 1.76 | 3AA2400 |
| K | 9 X 51 | 115 | 96 | 43.8 / 1.55 | 3AA2015 |
| B | 8.5 X 31 | 60 | 37.9 | 17.2 / 0.61 | 3AA2015 |
| C | 6 X 24 | 27 | 15.2 | 6.88 / 0.24 | 3AA2015 |
| D | 4 X 18 | 12 | 4.9 | 2.24 / 0.08 | 3AA2015 |
| AL | 8 X 53 | 52 | 64.8 | 29.5 / 1.04 | 3AL2015 |
| BL | 7.25 X 39 | 33 | 34.6 | 15.7 / 0.55 | 3AL2216 |
| CL | 6.9 X 21 | 19 | 13 | 5.9 / 0.21 | 3AL2216 |
| XL | 14.5 X 50 | 75 | 238 | 108 / 3.83 | 4BA240 |
| SSB | 8 X 37 | 95 | 41.6 | 18.9 / 0.67 | 3A1800 |
| 10S | 4 X 31 | 21 | 8.3 | 3.8 / 0.13 | 3A1800 |
| LB | 2 X 15 | 4 | 1 | 0.44 / 0.016 | 3E1800 |
| XF | 12 X 46 | 180 | | 60.9 / 2.15 | 8AL |
| XG | 15 X 56 | 149 | 278 | 126.3 / 4.46 | 4AA480 |
| XM | 10 X 49 | 90 | 120 | 54.3 / 1.92 | 3A480 |
| XP | 10 X 55 | 55 | 124 | 55.7 / 1.98 | 4BA300 |
| QT | 3 X 14 includes 4.5 inches for valve | 2.5 includes 1.5 lbs for valve | 2.0 | 0.900 / 0.0318 | 4B-240ET |
| LP5 | 12.25 X 18.25 | 18.5 | 47.7 | 21.68 / 0.76 | 4BW240 |
| Medical E | 4 x 26 excludes valve and cap | 14 excludes valve and cap | | 4.5 / 0.16 | 3AA2015 |

Chapter 9

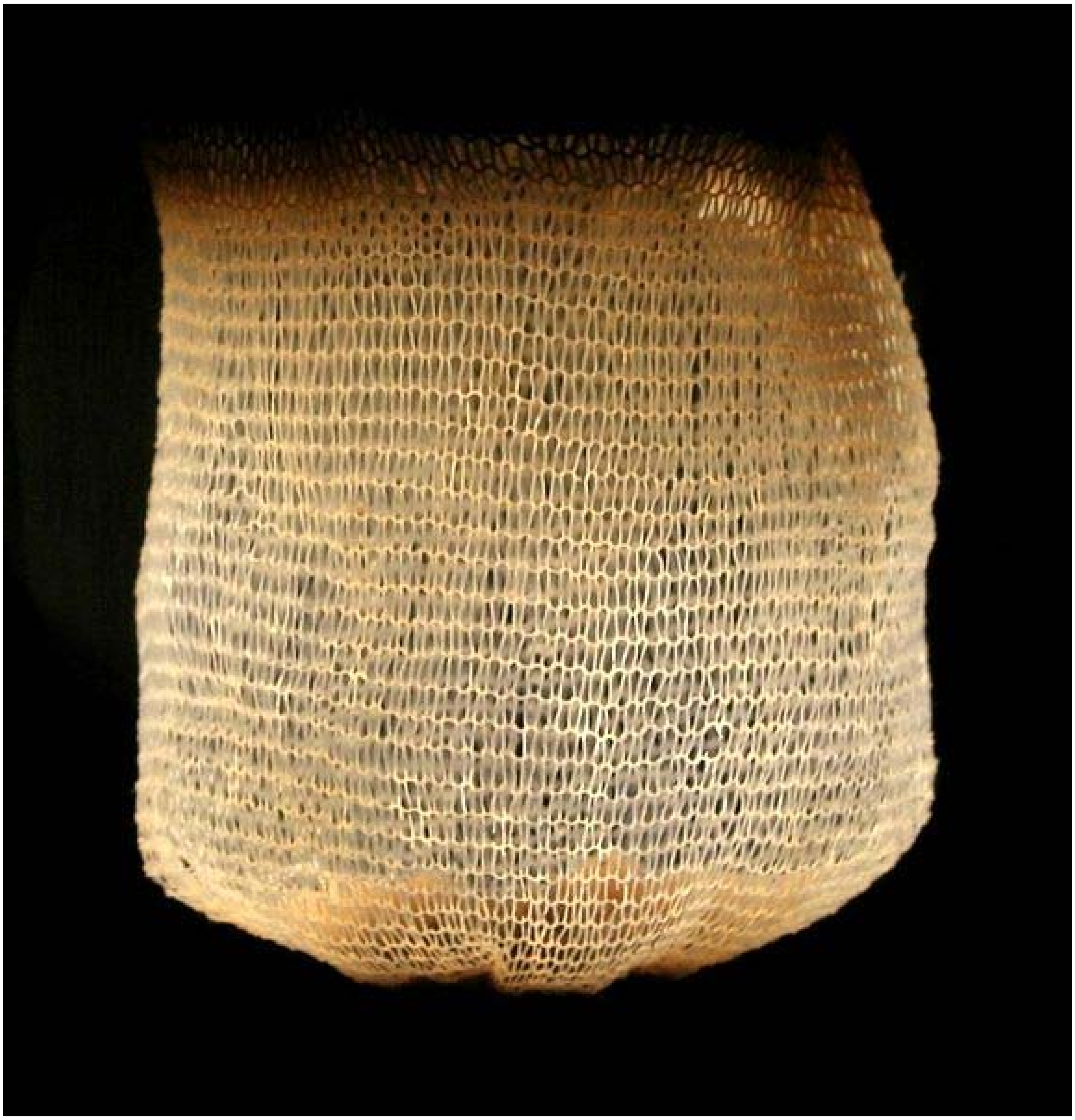
# Gas Mantle and Gas Stove

## Gas mantle

An **incandescent gas mantle**, **gas mantle**, or **Welsbach mantle** is a device for generating bright white light when heated by a flame. The name refers to its original heat source, existing gas lights, which filled the streets of Europe and North America in the late 19th century, mantle referring to the way it was hung above the flame. Today they are still used for portable camping lanterns and pressure lamps.

Mantles in their unused flat-packed form

### *Mechanism*



A Coleman white gas lantern mantle burning at full brightness

The mantle is made from oxides that, when heated, glow brightly in the visible spectrum while emitting little infrared radiation. The rare earth oxides (cerium) and actinide (thorium) in the mantle have a low emissivity in the infrared (in comparison with an ideal black body), but have high emissivity in the visible spectrum. This is because of candoluminescence. Hence, when heated by a kerosene or liquified petroleum gas flame, the mantle emits radiation that is weighted less heavily in the infrared and more heavily in the visible spectrum, leading to an enhanced output of useful light.

Modern mantles are made by saturating a ramie-based artificial silk or rayon fabric with rare earths. When the mantle, which resembles a small net bag, is placed in the flame for the first time, the fabric burns away, leaving a residue of metal oxide, which glows brightly.

The mantle shrinks and becomes very fragile after this first use.

The mantle also aids the combustion process, keeping the flame small at higher flow rates than in a simple lamp. This concentration of combustion near the mantle, in turn, improves the transfer of heat from the flame to the mantle.

## *History*

For centuries, artificial light had been generated using open flames. Limelight had been invented in the 1820s, but the temperature required was too high to be practical for small lights. In the late 19th century several inventors tried to develop an effective alternative based on heating a material to a lower temperature but using spectral lines to simulate white light.

Many early attempts used platinum-iridium gauze soaked in metal nitrates, but were not successful because of high cost materials and poor reliability.

The first effective mantle was the *Clamond basket* in 1881, named after its inventor. It was exhibited in the Crystal Palace exhibition of 1883. This device was made from a mixture of magnesium hydrate, magnesium acetate and water which was squeezed through holes in a plate to form threads, which were then moulded into a basket shape and ignited. The acetate burnt, the combustion products forming a matrix to support the magnesium oxide formed as the hydrate decomposed. The fragile structure was supported by a platinum wire cage and heated by a coal gas flame.

The modern gas mantle was one of the many inventions of Carl Auer von Welsbach, a chemist who studied rare earth elements in the 1880s and who had been Robert Bunsen's student. Ignaz Kreidl worked with him on his early experiments to create the Welsbach mantle. His first process used a mixture of 60% magnesium oxide, 20% lanthanum oxide and 20% yttrium oxide, which he called *Actinophor*, and patented in 1885.

The original mantles gave off a green-tinted light and were not very successful, and his first company, which established a factory in Atzgersdorf in 1887, failed in 1889. In 1890 he discovered that thorium was superior to magnesium, and in 1891 perfected a new mixture of 99% thorium dioxide and 1% cerium dioxide that gave off a much whiter light and produced a stronger mantle. After introducing it commercially in 1892 it quickly spread throughout Europe. The gas mantle remained an important part of street lighting until the widespread introduction of electric lighting in the early 1900s.

To produce a mantle, cotton is woven into a net bag and impregnated with the soluble nitrates of these metals and then heated; the cotton burns away and the nitrates are converted to nitrites, which fuse together to form the solid mesh. As the heating continues, the nitrites decompose into the final solid, (but fragile) very high melting point oxides.

Early mantles were sold in the unheated cotton mesh condition, since the oxide structure was too fragile to transport easily, and the purchaser carried out the conversion when it was first used. The cotton quickly rotted because of the corrosive nature of the acidic metal nitrates (although was later reduced by soaking the mantle in ammonia solution to neutralise the excess acid).

Later mantles were made from guncotton (nitrocellulose) or collodion rather than ordinary cotton, since extremely fine threads of it could be produced; it was converted back to cellulose before heating (since these materials are highly flammable or explosive) by dipping in ammonium sulfide.

It was discovered that the finished mantle could be strengthened sufficiently by dipping in a solution of collodion, which would coat it with a thin layer of the material to be burnt off when the mantle was first used, although modern mantles are now usually sold in their original fabric condition.

Early mantles often had a binding thread of asbestos for tying onto the lamp fitting, but because of its carcinogenic properties it has been replaced with wire or ceramic fiber thread in modern mantles.

## *Safety of thorium*

Since thorium is radioactive and produces a radioactive gas, radon-220, as one of its decay products, there are concerns about the safety of thorium mantles. Some nuclear safety agencies make recommendations about their use . A study in 1981 estimated that the dose from using a thorium mantle every weekend for a year would be 0.3-0.6 millirems, tiny in comparison to the normal annual dose of a few hundred millirems, although a person ingesting an entire mantle would receive a comparable dose of 200 mrem (2 mSv; , ). However, the radioactivity is a major concern for those people involved with the manufacture of mantles and with contamination of soil around some former factory sites . All of these issues have meant that alternatives, usually yttrium or sometimes zirconium, are used in some countries although they are either more expensive or less efficient.

One potential cause for concern is that particles from thorium gas mantles "fall out" over time and get into the air, where they may be ingested in food or drink. These particles can also be inhaled and remain in the lungs or liver. Also of concern is the release of thorium bearing dust if the mantle shatters due to mechanical impact.

# Gas stove

Many stoves use natural gas to provide heat.

In cooking, a **gas stove** is a cooker which uses natural gas, propane, butane, liquefied petroleum gas or other flammable gas as a fuel source.

## *History*

The first gas stoves were developed as early as the 1820s, but these remained isolated experiments. James Sharp patented a gas stove in Northampton, England in 1826 and opened a gas stove factory in 1836. At the World Fair in London in 1851, a gas stove was shown, but only in the 1880s did this technology start to become a commercial success. The main factor for this delay was the slow growth of the gas pipe network.

The first gas stoves were rather unwieldy, but soon the oven was integrated into the base and the size reduced to fit in better with the rest of the kitchen furniture. In the 1910s, producers started to enamel their gas stoves for easier cleaning. A high-end gas stove called the AGA cooker was invented in 1922 by Swedish Nobel prize winner Gustaf Dalén.

## *Ignition*

Gas stoves today use two basic types of ignition sources, standing pilot and electric. A stove with a standing pilot has a small, continuously burning gas flame (called a pilot flame) under the cooktop. The flame is between the front and back burners. When the stove is turned on, this flame lights the gas flowing out of the burners. The advantage of the standing pilot system is that it is simple and completely independent of any outside power source. A minor drawback is that the flames continuously consume fuel even when the stove is not in use. Early gas ovens did not have a pilot. One had to light these manually with a match [Stove Lighting]. If one accidentally left the gas on, gas would fill the oven and eventually the room. A small spark, such as an arc from a light switch being turned on, could ignite the gas, triggering a violent explosion. To prevent these types of accidents, oven manufacturers developed and installed a safety valve in the oven. The safety valve uses a pilot flame to ignite the main burner when the oven is turned on. The pilot flame heats a thermocouple that sends a signal to the valve to stay open. If a draft blows out the pilot flame or it goes out due to loss of gas pressure, the thermocouple cools and signals the valve to close, shutting off the gas to the oven.

A modern ignited gas stove

Electric ignition stoves use electric sparks to ignite the surface burners. This is the "clicking sound" audible just before the burner actually lights. The sparks are initiated by turning the gas burner knob to a position typically labeled "LITE." Once the burner lights, the knob is turned further to modulate the flame size. Auto reignition is an elegant refinement: the user need not know or understand the wait-then-turn sequence. They simply turn the burner knob to the desired flame size and the sparking is turned off automatically when the flame lights. Auto reignition also provides a safety feature: the flame will be automatically reignited if the flame goes out while the gas is still on--for example by a gust of wind. If the power fails, surface burners must be manually match-lit. Electric ignition for ovens uses a "hot surface" or "glow bar" ignitor. Basically it is a heating element that heats up to gas's ignition temperature. A sensor detects when the glow bar is hot enough and opens the gas valve.

## Chapter 10

# Pneumatics

Preserved Porter Locomotive Company No. 3290 of 1923.

**Pneumatics** is a branch of technology, which deals with the study and application of use of pressurized gas to affect mechanical motion.

Pneumatic systems are extensively used in industry, where factories are commonly plumbed with compressed air or other compressed inert gases. This is because a centrally-located and electrically-powered compressor that powers cylinders and other pneumatic devices through solenoid valves is often able to provide motive power in a cheaper, safer, more flexible, and more reliable way than a large number of electric motors and actuators.

Pneumatics also has applications in dentistry, construction, mining, and other areas.

### *Examples of pneumatic systems and components*

- Air brakes on buses and trucks
- Air brakes, on trains
- Air compressors
- Air engines for pneumatically powered vehicles
- Barostat systems used in Neurogastroenterology and for researching electricity
- Cable jetting, a way to install cables in ducts
- Compressed-air engine and compressed-air vehicles
- Gas-operated reloading
- Holman Projector, a pneumatic anti-aircraft weapon
- Lego pneumatics can be used to build pneumatic models

- Pipe organs:
    - Electro-pneumatic action
    - Tubular-pneumatic action

- Pneumatic actuator
- Pneumatic air guns
- Pneumatic cylinder
- Pneumatic Launchers, a type of spud gun
- Pneumatic mail systems
- Pneumatic motor
- Pneumatic tire

- Pneumatic tools:
    - Jackhammer used by road workers
    - Pneumatic nailgun

- Pressure regulator
- Pressure sensor
- Pressure switch

- Vacuum pump

### *Gases used in pneumatic systems*

Pneumatic systems in fixed installations such as factories use compressed air because a sustainable supply can be made by compressing atmospheric air. The air usually has moisture removed and a small quantity of oil added at the compressor, to avoid corrosion of mechanical components and to lubricate them.

Factory-plumbed, pneumatic-power users need not worry about poisonous leakages as the gas is commonly just air. Smaller or stand-alone systems can use other compressed gases which are an asphyxiation hazard, such as nitrogen - often referred to as OFN (oxygen-free nitrogen), when supplied in cylinders.

Any compressed gas other than air is an asphyxiation hazard - including nitrogen, which makes up 77% of air. Compressed oxygen (approx. 23% of air) would not asphyxiate, but it would be an extreme fire hazard, so is never used in pneumatically powered devices.

Portable pneumatic tools and small vehicles such as Robot Wars machines and other hobbyist applications are often powered by compressed carbon dioxide because containers designed to hold it such as soda stream canisters and fire extinguishers are readily available, and the phase change between liquid and gas makes it possible to obtain a larger volume of compressed gas from a lighter container than compressed air would allow. Carbon dioxide is an asphyxiant and can also be a freezing hazard when vented inappropriately.

## *Comparison to hydraulics*

Both pneumatics and hydraulics are applications of fluid power. Pneumatics uses an easily compressible gas such as air or a suitable pure gas, while hydraulics uses relatively incompressible liquid media such as oil. Most industrial pneumatic applications use pressures of about 80 to 100 pounds per square inch (550 to 690 kPa). Hydraulics applications commonly use from 1,000 to 5,000 psi (6.9 to 34 MPa), but specialized applications may exceed 10,000 psi (69 MPa).

### Advantages of pneumatics

- **Simplicity of Design And Control**
    - Machines are easily designed using standard cylinders & other components. Control is as easy as it is simple ON - OFF type control.
- **Reliability**
    - Pneumatic systems tend to have long operating lives and require very little maintenance.
    - Because gas is compressible, the equipment is less likely to be damaged by shock. The gas in pneumatics absorbs excessive force, whereas the fluid of hydraulics directly transfers force.
- **Storage**
    - Compressed Gas can be stored, allowing the use of machines when electrical power is lost.
- **Safety**
    - Very low chance of fire (compared to hydraulic oil).
    - Machines can be designed to be overload safe.

### Advantages of hydraulics

- Liquid (as a gas is also a 'fluid') does not absorb any of the supplied energy.
- Capable of moving much higher loads and providing much higher forces due to the incompressibility.
- The hydraulic working fluid is basically incompressible, leading to a minimum of spring action. When hydraulic fluid flow is stopped, the slightest motion of the load releases the pressure on the load; there is no need to "bleed off" pressurized air to release the pressure on the load.

## *Pneumatic logic*

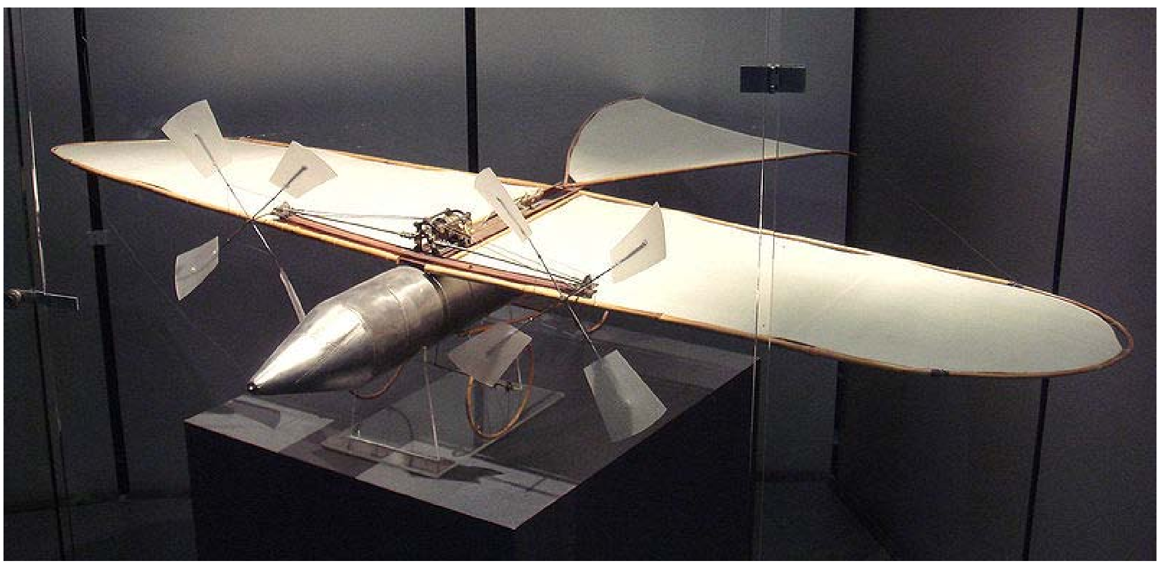
Pneumatic logic systems (sometimes called **air logic control**) are often used to control industrial processes, consisting of primary logic units such as:

- And Units
- Or Units
- 'Relay or Booster' Units
- Latching Units
- 'Timer' Units
- Sorteberg relay
- fluidics amplifiers with no moving parts other than the air itself

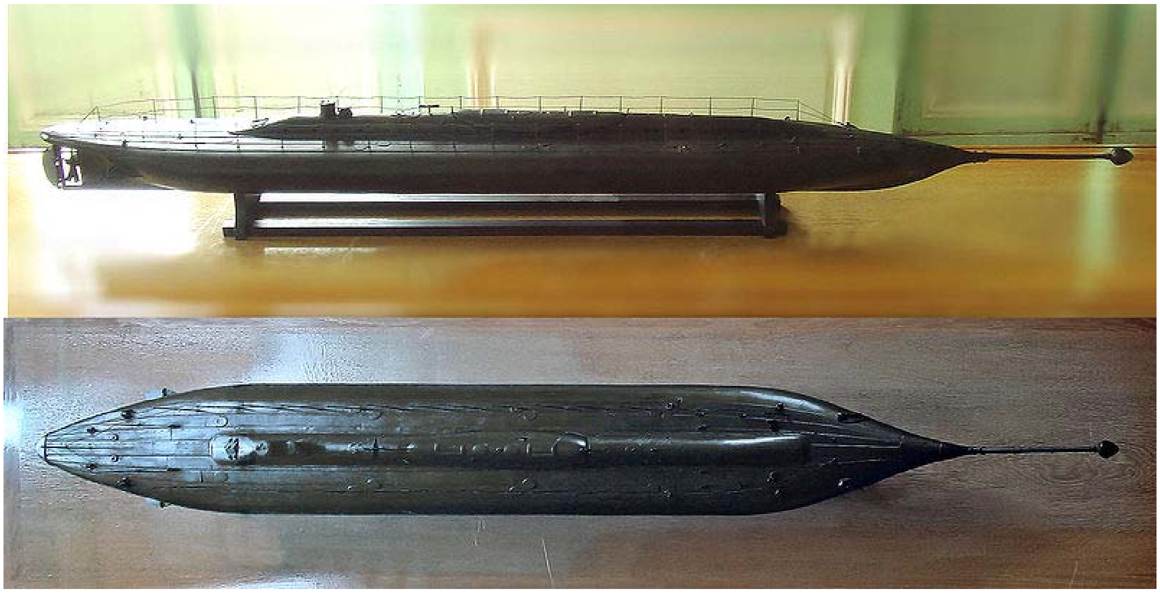
Pneumatic logic is a reliable and functional control method for industrial processes. In recent years, these systems have largely been replaced by electrical control systems, due to the smaller size and lower cost of electrical components. Pneumatic devices are still used in processes where compressed air is the only energy source available or upgrade cost, safety, and other considerations outweigh the advantage of modern digital control.

# Chapter 11

# Pneumatic Motor



The Victor Tatin airplane of 1879 used a compressed-air engine for propulsion. Original craft, at Musée de l'Air et de l'Espace.



The first mechanically-powered submarine, the 1863 *Plongeur*, used a compressed-air engine. Musée de la Marine (Rochefort).

A **pneumatic motor** or **compressed air engine** is a type of motor which does mechanical work by expanding compressed air. Pneumatic motors generally convert the compressed air to mechanical work through either linear or rotary motion. Linear motion can come from either a diaphragm or piston actuator, while rotary motion is supplied by either a vane type air motor or piston air motor.

Pneumatic motors have existed in many forms over the past two centuries, ranging in size from hand held turbines to engines of up to several hundred horsepower. Some types rely on pistons and cylinders, others use turbines. Many compressed air engines improve their performance by heating the incoming air, or the engine itself. Pneumatic motors have found widespread success in the hand-held tool industry and continual attempts are being made to expand their use to the transportation industry. However, pneumatic motors must overcome inefficiencies before being seen as a viable option in the transportation industry.

## *Classification*

### Linear

In order to achieve linear motion from compressed air, a system of pistons is most commonly used. The compressed air is pumped into an air-tight chamber that houses the shaft of the piston. Also inside this chamber a spring is coiled around the shaft of the piston in order to hold the chamber completely open when air is not being pumped into the chamber. As air is pumped into the chamber the force on the piston shaft begins to overcome the force being exerted on the spring. As more air is pumped into the chamber, the pressure increases and the piston begins to move down the chamber. When it reaches its maximum length the air pressure is released from the chamber and the spring completes the cycle by closing off the chamber to return to its original position.

Piston motors are the most commonly used in hydraulic systems. Essentially, piston motors are the same as hydraulic pumps except they are used to convert hydraulic energy into mechanical energy. Piston motors are often used in series of two, three, four, five, or six cylinders that are enclosed in a housing. This allows for more power to be delivered by the pistons because several motors are in sync with each other at certain times of their cycle.

### Rotary

Another type of pneumatic motor, known as a rotary vane motor, uses air to produce rotational motion to a shaft. The rotating element is a slotted rotor which is mounted on a drive shaft. Each slot of the rotor is fitted with a freely sliding rectangular vane. The vanes are extended to the housing walls using springs, cam action, or air pressure, depending on the motor design. Air is pumped through the motor input which pushes on the vanes creating the rotational motion of the central shaft. Rotation speeds can vary between 100 and 25,000 rpm depending on several factors which including the amount of air pressure at the motor inlet and the diameter of the housing.

Rotary motion vane-type air motors are used to start large industrial diesel or natural gas engines. Stored energy in the form of compressed air, nitrogen or natural gas enters the sealed motor chamber and exerts pressure against the vanes of a rotor. Much like a windmill, this causes the rotor to turn at high speed. Because the engine flywheel requires a great deal of torque to start the engine, reduction gears are used. Reduction gears to create high torque levels with the lower amounts of energy input. These reduction gears allow for sufficient torque to be generated by the engine flywheel while it is engaged by the pinion gear of the air motor or air starter.

## *Application*

A widespread application of small pneumatic motors is in hand-held tools, power ratchet wrenches, drills, sanders, grinders, cutters, and so on. Though overall energy efficiency of pneumatics tools is low and they require access to a compressed-air source, there are several advantages over electric tools. They offer greater power density (a smaller pneumatic motor can provide the same amount of power as a larger electric motor), do not require an axillary speed controller (adding to its compactness), generate less heat, and can be used in more volatile atmospheres as they do not require electric power.

Historically, many individuals have tried to apply pneumatic motors to the transportation industry. Guy Negre, CEO and founder of Zero Pollution Motors, has pioneered this field since the late 1980s. Recently Engineair has also developed a rotary motor for use in automobiles. Engineair places the motor immediately beside the wheel of the vehicle and uses no intermediate parts to transmit motion which means almost all of the motor's energy is used to rotate the wheel.

## *History in transportation*

The pneumatic motor was first applied to the field of transportation in the mid-19th century. Though little is known about the first recorded compressed-air vehicle, it is said that the Frenchmen Andraud and Tessie of Motay ran a car powered by a pneumatic motor on a test track in Chaillot, France, on July 9, 1840. Although the car test was reported to have been successful, the pair didn't explore further expansion of the design.

The first successful application of the pneumatic motor in transportation was the Mekarski system air engine used in locomotives. Mekarski's innovative engine overcame cooling that accompanies air compression by heating air in a small boiler prior to use. The Tramway de Nantes, located in Nantes, France, was noted for being the first to use Mekarski engines to power their fleet of locomotives. The tramway began operation on December 13, 1879, and continues to operate today, although the pneumatic trams were replaced in 1917 by more efficient and modern electrical trams.

American Charles Hodges also found success with pneumatic motors in the locomotive industry. In 1911 he designed a pneumatic locomotive and sold the patent to the H. K. Porter Company in Pittsburgh for use in coal mines. Because pneumatic motors do not use combustion they were a much safer option in the coal industry.

Many companies claim to be developing Compressed air cars, but none are actually available for purchase or even independent testing.

## *Tools*

Impact wrenches, drills, firearms, die grinders, dental drills and other pneumatic tools use a variety of air engines or motors. These include vane type pumps, turbines and pistons.

## *Torpedoes*

Most successful early forms of self propelled torpedoes used high pressure compressed air, although this was superseded by internal or external combustion engines, steam engines, or electric motors.

### *Railways*

Pneumatic Locomotive with attached pressure container used during the construction of the Gotthard Rail Tunnel 1872-1880.


A compressed air locomotive by H. K. Porter, Inc., in use at the Homestake Mine, South Dakota, between 1928 and 1961

Compressed air engines were used in trams and shunters, and eventually found a successful niche in mining locomotives, although eventually they were replaced by electric trains, underground. Over the years designs increased in complexity, resulting in a triple expansion engine with air-to-air reheaters between each stage.

## *Aircraft*

Transport category airplanes, such as commercial airliners, use compressed air starters to start the main engines. The air is supplied by the load compressor of the aircraft's auxiliary power unit, or by ground equipment.

## *Automotive*

There is currently some interest in developing air cars. Several engines have been proposed for these, although none have demonstrated the performance and long life needed for personal transport.

### Energine

The Energine Corporation is a South Korean company that delivers fully-assembled cars running on a hybrid compressed air and electric engine. The compressed-air engine is used to activate an alternator, which extends the autonomous operating capacity of the car.

### EngineAir

EngineAir, an Australian company, is making a rotary engine powered by compressed air, called The Di Pietro motor. The Di Pietro motor concept is based on a rotary piston. Different from existing rotary engines, the Di Pietro motor uses a simple cylindrical rotary piston (shaft driver) which rolls, with little friction, inside the cylindrical stator.

It can be used in boat, cars, carriers and other vehicles. Only 1 psi (≈ 6,8 kPa) of pressure is needed to overcome the friction. The engine was also featured on the ABC's New Inventors program in Australia on the 24th March, 2004.

### K'Airmobiles

K'Airmobiles vehicles were intended to be commercialized from a project developed in France in 2006-2007 by a small group of researchers. However, the project has not been able to gather the necessary funds.

People should note that, meantime, the team has recognized the physical impossibility to use on-board stored compressed air due to its poor energy capacity and the thermal losses resulting from the expansion of the gas.

These days, using the patent pending 'K'Air Generator', converted to work as a compressed-gas motor, the project should be launched in 2010, thanks to a North

American group of investors, but for the purpose of developing first a green energy power system.

## MDI

In the original Nègre air engine, one piston compresses air from the atmosphere to mix with the stored compressed air (which will cool drastically as it expands). This mixture drives the second piston, providing the actual engine power. MDI's engine works with constant torque, and the only way to change the torque to the wheels is to use a pulley transmission of constant variation, losing some efficiency. When vehicle is stopped, MDI's engine had to be on and working, losing energy. In 2001-2004 MDI switched to a design similar to that described in Regusci's patents, which date back to 1990.

It has been reported in 2008 that Indian car manufacturer Tata was looking at an MDI compressed air engine as an option on its low priced Nano automobiles. Tata announced in 2009 that the compressed air car was proving difficult to develop due to its low range and problems with low engine temperatures.

## Quasiturbine

The **Pneumatic Quasiturbine** engine is a compressed air pistonless rotary engine using a rhomboidal-shaped rotor whose sides are hinged at the vertices.

The Quasiturbine has demonstrated as a pneumatic engine using stored compressed air

It can also take advantage of the energy amplification possible from using available external heat, such as solar energy.

The Quasiturbine rotates from pressure as low as 0.1 atm (1.47psi).

Since the Quasiturbine is a pure expansion engine, while the Wankel and most other rotary engines are not, it is well-suited as a compressed fluid engine, air engine or air motor.

## Regusci

Armando Regusci's version of the air engine couples the transmission system directly to the wheel, and has variable torque from zero to the maximum, enhancing efficiency. Regusci's patents date from 1990.

## Team Psycho-Active

Psycho-Active is developing a multi-fuel/air-hybrid chassis which is intended to serve as the foundation for a line of automobiles. Claimed performance is 50 hp/litre.

## *Defunct Air Engine Designs*

### Conger Motor

Milton M. Conger in 1881 patented and supposedly built a motor that ran off compressed air or steam that using a **flexible tubing** which will form a wedge-shaped or inclined wall or abutment in the rear of the tangential bearing of the wheel, and propel it with greater or less speed according to the pressure of the propelling medium.

# Chapter 12

# Lego Pneumatics

| Lego Pneumatics | |
|---|---|
| **Parent theme** | Lego Technic |
| **Availability** | 1984– |
| **Total sets** | Pneumatics Add-On Set (W979641) & Pneumatics Extension Pack (W991462) |


Lego Pneumatic Components

**Lego pneumatics** is a variety of Lego bricks which use air pressure and specialised components to perform various actions using the principles of pneumatics.

## *History*

The LEGO pneumatics components were first introduced as part of the LEGO Technic range in 1984. Since their introduction, LEGO pneumatics have featured in a variety of LEGO Technic and LEGO Educational (DACTA) products.

### Generation 1

The first generation of LEGO Pneumatics ran from 1984 through 1988. This generation was simple compared to the later generations. The pneumatic cylinders, for example, only had one input valve. This meant that in a simple pump->switch->cylinder setup, the cylinder rod could only push outwards, requiring gravity to pull it back in.

A pneumatic distribution block piece was utilised (along with a switch) in order to enable pulling as well by creating vacuum instead of pressure in the cylinder, however, this had limitations and often made pneumatic circuits quite complex.

### Generation 2

In 1989, the LEGO pneumatic line was revamped, and a new cylinder and pump piece were introduced. The old cylinders and pumps were discontinued. The chief difference is that the new cylinder had two input valves now, which allowed both pushing and pulling without needing complex circuits involving the distribution block piece.

Over the years, several new pieces were introduced in this line as well. The new pump was spring based, and could only be operated by hand, which limited pneumatic power to how fast it could be manually pumped. This obviously limited the power of pneumatic circuits. So in 1992, LEGO introduced two new pieces; a small pump and a small cylinder. The small pump did not have a spring on it, and it was designed to be operated by a motor, which would allow for continuously-running pneumatic creations. As of 2011, the small pump has only appeared in two model sets — 8868 Air Tech Claw Rig (1992) and 8049 Tractor with Log Loader (2010) (both found on Peeron) — and a few parts sets (no longer available).

In 1997, LEGO introduced the Air Tank, which acts like a battery, storing compressed air so that even more powerful pneumatic circuits can be created. This piece is very popular with the enthusiast community, but many feel that it was underutilised by LEGO, as it only appeared in 3 model sets and a parts pack. This tank is now only available at the LEGO Education Store, along with a new manometer part.

In 2003, LEGO discontinued the old cylinder and switch parts, and made new "studless" versions to fit in with their transition towards removing studs from Technic sets.

### Linear Actuator

Beginning 2008, LEGO has released several sets with mechanical linear actuators, which are used for the same purpose as the pneumatic cylinders, but the fact that they can easily be extended to intermediate points means that they approximate hydraulic cylinders more closely.

## *Lego pneumatics components*

The key components of Lego pneumatics are:

**Pneumatic pump**

There are three versions of the pump. The old Generation 1 pump, the new Generation 2 pump (both of these are spring-loaded) and the small pump without a spring (designed for use with motors). The Gen. 1 pump is red, while the Gen. 2 pump is yellow and has a larger contact pad at the top of the pump.

Pumps are the primary source of air in a pneumatic circuit.

**Pneumatic cylinder**

Cylinders look like pumps, but they are the outputs of the energy, rather than the inputs. There are five versions of cylinders. The Generation 1 cylinders came in two lengths, only had one input and thus were limited in how they could be used. The Generation 2 cylinders have 2 inputs (and come in studded, studless, and small versions), and allow pushing and pulling, depending on which input air is pumped into.

**Pneumatic switch**

Switches have three ports on them, and a Lego axle which controls which of the ports are connected to each other.

| Switch | Left Port | Middle Port | Right Port |
|---|---|---|---|
| Left position | Open | Connected to Right | Connected to Center |
| Middle Position | Closed | Closed | Closed |
| Right position | Connected to Center | Connected to Left | Open |

When a port is "open", that means it is like an open tire valve; all the air will leak out as fast as it can. When a port is closed, no air can enter or leave that port. When ports are connected, air will freely travel through the switch between those two ports.

**Pneumatic tubing**

Tubing is simply the means by which air power is transferred through the circuit. Tubing can connect to a switch, air tank, T-junction, cylinder, pump, distribution block, or flex-hose.

Flex-hoses aren't actually considered pneumatic pieces; they were designed as part of the Technic system for a different purpose, but Lego fans have discovered that pneumatic tubing actually fits over flex hoses pretty well, so many people use them as tubing extenders whenever they are needed. Flex hoses are more rigid than tubing.

Lego pneumatic tubing almost always comes with sets in an uncut form, and are required to be cut into smaller pieces using scissors. On the new 8049 technic tractor and log loader, the tubes are already cut to size.

**Pneumatic T-junction**

A T-junction is a very small piece that allows three pieces of tubing to connect into one junction, essentially splitting (or joining) airflow from two hoses into one. These only allow 1:2 branching, but by combining T-junctions, any number of branches can be achieved (ie: one tube can branch into three by using two T-junctions).

**Air tank**

Air tanks are an important piece to most larger pneumatic designs, as they allow air power to be easily stored for later retrieval.

In 2006, Lego has discontinued this piece.

In 2008 Lego Education has re-released the tank in a new white color, as part of an add-on set (W979641)

**Pneumatic distribution block**

These pieces used a special kind of one-way valve inside of them, and three ports on the outside. The leftmost port could only have air going into it, no air would ever come out. The middle port could have air going in or out. The right port could only have air coming out of it, no air could go into it.

Using these, it was possible to make the Generation 1 cylinders pull down as well as push up, however the pulling wasn't as strong as the pushing, and this prompted Lego to redesign the pneumatics into an easier-to-use and stronger system.

These were discontinued when Lego switched to Generation 2, in 1988.

### *Pneumatic principles*

Lego pneumatics offer the opportunity to learn and experiment with the principles of pneumatics and control circuits. Advanced use of Lego pneumatics has been made in various Lego Mindstorms creations.

Lego pneumatic projects usually include a compressor made from a combination of a lego electric motor and pneumatic pump, together with a pressure switch which will activate the motor when greater pressure is required.

Because a slight delay is involved between increased pressure and cylinder movement, various feedback loops can be used whereby one pneumatic component can activate another in a series of mechanical events.

Lego pneumatics can be configured in such a way that electronic circuits can be replicated. These circuits can then be combined to create digital computers.

### *Alternative pneumatic systems*

Fischertechnik offers a similar pneumatics system for robotic and control technology hobbyists. The Fischertechnik system includes an electrically activated air solenoid, a feature not available in the Lego range.

A number of hobbyists have also constructed additional components such as larger air tanks and solenoids to complement the standard Lego pneumatic components.

# Chapter 13

# Electro-Pneumatic Action and Tubular-Pneumatic Action

## Electro-pneumatic action

The **electro-pneumatic action** is a control system for pipe organs, whereby air pressure, controlled by an electric current and operated by the keys of an organ console, opens and closes valves within wind chests, allowing the pipes to speak. This system also allows the console to be physically detached from the organ itself. The only connection was via an electrical cable from the console to the relay, with some early organ consoles utilizing a separate wind supply to operate combination pistons.

### *Invention*

Although early experiments with Barker lever, tubular-pneumatic and electro-pneumatic actions date as far back as the 1850s, credit for a feasible design is generally given to the English organist and inventor, Robert Hope-Jones. He overcame the difficulties inherent in earlier designs by including a rotating centrifugal air blower and replacing banks of batteries with a DC generator, which provided electrical power to the organ. This allowed the construction of new pipe organs without any physical linkages whatsoever. Previous organs used tracker action, which requires a mechanical linkage between the console and the organ windchests, or tubular-pneumatic action, which linked the console and windchests with a large bundle of lead tubing.

### *Operation*

When an organ key is depressed, an electric circuit is completed by means of a switch connected to that key. This causes a low-voltage current to flow through a cable to the windchest, upon which a rank, or multiple ranks of pipes are set. Within the chest, a small electro-magnet associated with the key that is pressed becomes energized. This causes a very small valve to open. This, in turn, allows wind pressure to activate a bellows or "pneumatic" which operates a larger valve. This valve causes a change of air pressure within a channel that leads to all pipes of that note. A separate "stop action" system is used to control the admittance of air or "wind" into the pipes of the rank or ranks selected by the organist's selection of stops, while other ranks are "stopped" from playing. the stop action can also be an electro-pneumatic action, or may be another type of action

This pneumatically assisted valve action is in contrast to a direct electric action in which each pipe's valve is opened directly by an electric solenoid which is attached to the valve.

### *Advantages and Disadvantages*

The console of an organ which uses either type of electric action is connected to the other mechanisms by an electrical cable. This makes it possible for the console to be placed in any desirable location. It also permits the console to be movable, or to be installed on a "lift", as was the practice with theater organs.

While many consider tracker action organs to be more sensitive to the player's control, others find some tracker organs heavy to play and tubular-pneumatic organs to be sluggish, and so prefer electro-pneumatic or direct electric actions.

An electro-pneumatic action requires less current or amperage to operate than a direct electric action. This causes less demand on switch contacts. An organ using electro-pneumatic action was more reliable in operation than early direct electric organs until improvements were made in direct electric components.

A disadvantage of an electro-pneumatic organ is its use of large quantities of thin perishable leather, usually lambskin. This requires an extensive "re-leathering" of the windchests every twenty-five to forty years depending upon the quality of the material used, the atmospheric conditions and the use of the organ.

Like tracker and tubular action, electro-pneumatic action is less flexible in operation than direct electric action, in which each rank operates independently, allowing "unification", where each individual rank on a windchest can be played at various octave ranges.

A drawback to older electric action organs was the large amount of wiring required for operation. With each stop tab and key being wired, the transmission cable could easily contain several hundred wires. The great number of wires required between the keyboards, the banks of relays and the organ itself, with each solenoid requiring its own signal wire, made the situation worse, especially if a wire was broken (this was particularly true with consoles located on lifts and/or turntables), which made tracing the break very difficult.

These problems increased with the size of the instrument, and it would not be unusual for a particular organ to contain over a hundred miles of wiring. The largest pipe organ in the world, the Boardwalk Hall Auditorium Organ, is said to contain more than 137,500 miles (221,300 km) of wire. Modern electronic switching has largely overcome these physical problems.

### *Modern methods*

In the years after the advent of the transistor, and later, integrated circuits and microprocessors, miles of wiring and electro-pneumatic relays have given way to electronic and computerized control and relay systems, which have made the control of pipe organs much more efficient. But for its time, the electro-pneumatic action was considered a great success, and even today modernized versions of this action are used in many new pipe organs.

# Tubular-pneumatic action

**"Tubular-pneumatic action"** refers to an apparatus used in many pipe organs built during the late 19th and early 20th centuries. The term "tubular" refers to the extensive use of lead tubing to connect the organ's console to the valves that control the delivery of "wind" (air under pressure) to the organ's pipes. Many such organs are extant 100 or more years after their construction.

Lead tubing of a 1910 Möller tubular-pneumatic pipe organ.

### *Description*

In any organ, each pipe has a valve located at its foot which responds to the organist's commands from the console's keyboard, pedalboard and stop controls. These valves are contained in windchests upon which the organ's pipework is set. Any type of apparatus that connects an organ's console with its windchest is referred to as its "action". An organ that utilizes tubular-pneumatic action is commonly called a "tubular-pneumatic organ".

## *Invention*

Until the advent of the tubular-pneumatic action, all organs used a system of levers and wooden rods called trackers to transmit the action of the keys and stops to the valves contained within the windchests. This necessitated a close proximity between the console and the chests. In 1845, Prosper-Antoine Moitessier, an organ-builder of Montpellier, France, patented the tubular-pneumatic system which allowed the console to be at a much greater distance from the organ pipes. Cavaillé-Coll, Henry Willis and Edwin Horsell Pulbrook were pioneers in perfecting and introducing the pneumatic action. The development of the tubular-pneumatic type of organ marked the first departure from the tracker organ style of construction that had been used for hundreds of years.

## *Operation*

The operation of a tubular-pneumatic organ is accomplished by a change of air pressure within lead tubes of about $\frac{1}{4}$ in (0.6 cm) inside diameter that connect the organ's console to its windchest. A separate tube is needed for each manual key, pedal key and stop control on the console. A large four manual organ can require over 300 individual tubes.

Two basic types of tubular-pneumatic actions were used: the "pressure" system and the more popular "exhaust" system. Both use three major components for each key and stop: a valve (within the console), a pneumatic (within the windchest), and a lead tube that connects them.

In the pressure system, the air in the tube and the pneumatic are normally at atmospheric pressure. Depressing a key increases the pressure in the tube, inflating the pneumatic, which opens the pipe's valve.

In the exhaust system, the pneumatic and tube normally contain windchest pressure. Depressing a key lets this pressure exhaust, which collapses the pneumatic and opens the pipe's valve.

## *Advantages and Disadvantages*

The advantages of the tubular-pneumatic action over the mechanical tracker action are a lightness of touch and the flexibility of console location. Although the latter was a great improvement over the tracker organ, the console location was still limited to around 50 ft (20 m) from the pipework.

While some considered the tubular-pneumatic action to be a great achievement in organ building, others thought just the opposite. Sir John Stainer, organist at St. Paul's, called it a "triumph of mechanical skill", while the eminent English organist W. T. Best called it "a complete failure; you cannot play a triplet on the Trumpet, and I consider it the most damnnable invention ever placed inside an organ".

The major disadvantage of tubular-pneumatic action is its sluggish response. This becomes more prevalent as the distance between the console and the pipework is increased. In organs whose divisions are located at various distances from the console, this slow response causes an undesirable time lag between the speech of the divisions.

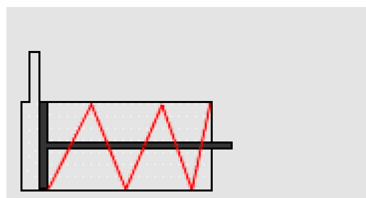
Another disadvantage over a tracker action organ is a lack of "feel" and control of attack by the organist, a trait that is present in all non-tracker action organs.

### *Decline of usage*

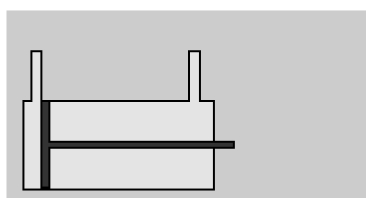
With the application of electric power to pipe organ action, the use of tubular-pneumatic action quickly declined. An organ with electro-pneumatic action or direct electric action has the lightness of touch of a tubular-pneumatic organ, but a faster response, and the console can be in any remote location. The console can also be movable, with only a cable connecting it to the rest of the organ.

# Chapter 14

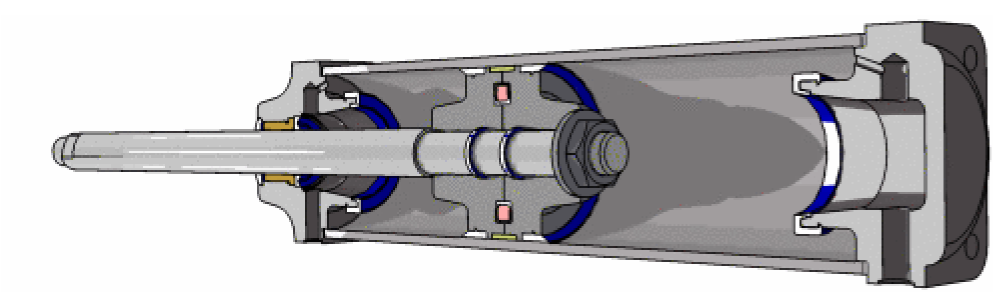
# Pneumatic Cylinder



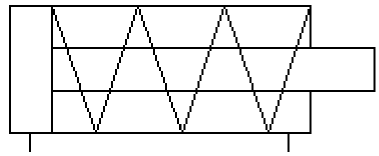
Operation diagram of a single acting cylinder. The spring (red) can also be outside the cylinder, attached to the item being moved.



Operation diagram of a double acting cylinder



Pneumatic cylinder (CAD)



Schematic symbol for pneumatic cylinder with spring return

**Pneumatic cylinders** (sometimes known as **air cylinders**) are mechanical devices which produce force, often in combination with movement, and are powered by compressed gas (typically air).

To perform their function, pneumatic cylinders impart a force by converting the potential energy of compressed gas into kinetic energy. This is achieved by the compressed gas being able to expand, without external energy input, which itself occurs due to the pressure gradient established by the compressed gas being at a greater pressure than the atmospheric pressure. This air expansion forces a piston to move in the desired direction. The piston is a disc or cylinder, and the piston rod transfers the force it develops to the object to be moved.

**A note about popular terminology**

At least in the USA, popular usage sometimes refers to the whole assembly of cylinder, piston, and piston rod (or more) collectively as a "piston", which is incorrect. See, for instance, "Hydraulic piston raises the table from 19 (in.) to 26 (in.)" Marine Tables, Inc. (Select item 3 of 8, near the bottom.)

## *Operation*

### General

Once actuated, compressed air enters into the tube at one end of the piston and, hence, imparts force on the piston. Consequently, the piston becomes displaced (moved) by the compressed air expanding in an attempt to reach atmospheric pressure.

### Fail safe mechanisms

Pneumatic systems are often found in settings where even rare and brief system failure is unacceptable. In such situations locks can sometimes serve as a safety mechanism in case of loss of air supply (or its pressure falling) and, thus, remedy or abate any damage arising in such a situation. Due to the leakage of air from input or output reduces the pressure and so the desired output.

## *Types*

Although pneumatic cylinders will vary in appearance, size and function, they generally fall into one of the specific categories shown below. However there are also numerous other types of pneumatic cylinder available, many of which are designed to fulfill specific and specialised functions.

### Single acting cylinders

Single acting cylinders (SAC) use the pressure imparted by compressed air to create a driving force in one direction (usually out), and a spring to return to the "home" position.

### Double acting cylinders

Double Acting Cylinders (DAC) use the force of air to move in both extend and retract strokes. They have two ports to allow air in, one for outstroke and one for instroke.

### Other types

Although SACs and DACs are the most common types of pneumatic cylinder, the following types are not particularly rare:

- Rotary air cylinders: actuators that use air to impart a rotary motion
- Rodless air cylinders: These have no piston rod. They are actuators that use a mechanical or magnetic coupling to impart force, typically to a table or other body that moves along the length of the cylinder body, but does not extend beyond it.

**Rodless cylinders**

Some rodless types have a slot in the wall of the cylinder. That slot is closed off for much of its length by two flexible metal sealing bands. The inner one prevents air from escaping, while the outer one protects the slot and inner band. The piston is actually a pair of them, part of a comparatively long assembly. They seal to the bore and inner band at both ends of the assembly. Between the individual pistons, however, are camming surfaces that "peel off" the bands as the whole sliding assembly moves toward the sealed volume, and "replace" them as the assembly moves away from the other end. Between the camming surfaces is part of the moving assembly that protrudes through the slot to move the load. Of course, this means that the region where the sealing bands are not in contact is at atmospheric pressure.

Another type has cables (or a single cable) extending from both (or one) end[s] of the cylinder. The cables are jacketed in plastic (nylon, in those referred to), which provides a smooth surface that permits sealing the cables where they pass through the ends of the cylinder. Of course, a single cable has to be kept in tension. .

Still others have magnets inside the cylinder, part of the piston assembly, that pull along magnets outside the cylinder wall. The latter are carried by the actuator that moves the load. The cylinder wall is thin, to ensure that the inner and outer magnets are near each other. Multiple modern high-flux magnet groups transmit force without disengaging or excessive resilience.

## Sizes

Air cylinders are available in a variety of sizes and can typically range from a small 2.5 mm air cylinder, which might be used for picking up a small transistor or other electronic component, to 400 mm diameter air cylinders which would impart enough force to lift a car. Some pneumatic cylinders reach 1000 mm in diameter, and are used in place of hydraulic cylinders for special circumstances where leaking hydraulic oil could impose an extreme hazard.

**Pressure, radius, area and force relationships**

Although the diameter of the piston and the force exerted by a cylinder are related, they are not directly proportional to one another. Additionally, the typical mathematical relationship between the two assumes that the air supply does not become saturated. Due to the effective cross sectional area reduced by the area of the piston rod, the instroke force is less than the outstroke force when both are powered pneumatically and by same supply of compressed gas.

The relationship, between force on outstroke, pressure and radius, is as follows:

$$F = p(\pi r^2)$$

Cord

This is derived from the relationship, between force, pressure and **effective** *cross-sectional area*, which is:

F = p A\,

With the same symbolic notation of variables as above, but also *A* represents the effective cross sectional area.

On instroke, the same relationship between force exerted, pressure and *effective cross sectional area* applies as discussed above for outstroke. However, since the cross sectional area is less than the piston area the relationship between force, pressure and *radius* is different. The calculation isn't more complicated though, since the effective cross sectional area is merely that of the piston less that of the piston rod.

For instroke, therefore, the relationship between force exerted, pressure, radius of the piston, and radius of the piston rod, is as follows:

$$F = p(\pi r_1^2 - \pi r_2^2) = p\pi(r_1^2 - r_2^2)$$

Where:

$F$ represents the force exerted
$r_1$ represents the radius of the piston
$r_2$ represents the radius of the piston rod
$\pi$ is pi, approximately equal to 3.14159.

### Materials

The pneumatic cylinders designed for educational use typically have transparent outer sleeves (often plexiglass), so students can see the piston moving inside.

The pnuematic cylinders designed for cleanroom applications often use lubricant-free Pyrex glass pistons sliding inside graphite sleeves.

## Chapter 15

# Spud Gun

A pneumatic potato cannon

A **potato cannon** (also known as a *spud gun*) is a pipe-based cannon which uses air pressure (*pneumatic*), or *combustion* of a gaseous fuel, to launch projectiles at high speeds. They are built to fire chunks of potato, as a hobby, or to fire other sorts of projectiles, for practical use. The projectile can be dangerous and result in life-threatening injuries, including cranial fractures, if a person is hit.

## *Launcher types*

All spud guns propel projectiles down their barrels using pressurised gas in the same manner as a firearm (although at a much lower pressure). There are four basic ways that spud guns may achieve this:

- By the combustion of a gaseous fuel-air mixture; this is generally called a **combustion launcher**, and its pressure is limited primarily by the energy density of the fuel-air mixture (less than 100 psi (0.7 MPa) with all safe fuels).
- By the release of compressed gas (normally air) through a valve; such a launcher is typically referred to as a **pneumatic launcher**, and its power is limited primarily by the pressure of the air supply, be that from a compressor, manual pump or bottled gas.
- By the explosion of a dry ice bomb placed in the pipe before the projectile, generally referred to as a **dry ice bomb cannon**, these are limited in power by the materials and size of the dry ice bomb but firing pressures can be around 200–300 psi (1.4–2.1 MPa).
- By the combustion of a pre-pressurised fuel-air mixture; this is called a **hybrid launcher**, and yields higher pressures than that of a normal combustion spud gun, limited only by the construction of the launcher (generally a few hundred pounds-force per square inch).

### Combustion launchers

Combustion powered spud guns typically have the least complex designs, the four basic elements of which are:

- A fuel system
- A combustion chamber
- An ignition source
- A barrel

In order to fire, the operator loads a projectile into the barrel, adds fuel to the combustion chamber (for example aerosols or propane), and triggers the ignition source (often using a piezoelectric BBQ igniter). The fuel then ignites, creating hot expanding gases, and forcing the projectile out of the barrel. Distances vary greatly depending on many factors, including the type of fuel used, the efficiency of the fuel/air ratio, the combustion chamber/barrel ratio, and the flight characteristics of the projectile. Common distances vary from 100 to 200 metres (110 to 220 yd), and there is a reported case of a cannon exceeding 500 metres (550 yd) of range.

Advanced combustion launchers may include metered propane injection to ensure proper fueling, chamber fans to mix the fuel with the air and accelerate venting of the chamber after firing, multiple spark gaps (spark strips) to decrease combustion time, and high-voltage ignition sources (flyback circuits, stun guns, camera flashes, etc.).

Combustion launchers are usually less powerful than their pneumatic or hybrid counterparts.

## Pneumatic launchers


A large pneumatic design: The projectile is loaded in the muzzle (not pictured), which is then attached to the cannon (at 2). The air reservoir (3) is filled to 120 psi (0.83 MPa) using the Schrader valve (4). Upon opening the solenoid valve (1), the air from the reservoir is transferred to the projectile, which is fired out of the muzzle.

Pneumatic launchers are considered a little more difficult to build due to the need of a completely airtight construction. These cannons have four basic components:

- A filling valve
- An air chamber
- A pressure release valve
- A barrel

In a pneumatic spud gun, air is pumped into the pressure chamber. After the desired chamber pressure is reached, the pressure release valve is opened, allowing the gas to expand down the barrel, propelling the projectile forwards.

The filling valve is usually a commonly available type such as a Schrader or Presta valve but other assemblies to pressurise the cannon such as quick release connections with ball or check valves have been used.

The pressure release valve is often one of a variety of commercially available types such as a plumbing ball valve, an irrigation sprinkler valve or a quick exhaust valve. Experienced builders often make their own valves for this purpose to gain greater flow and faster actuation. The most common custom design used is the piston valve. Multiple valves arranged to be triggered together are occasionally used as an alternative to a single larger valve.

The range of pneumatic cannons is more variable than the range of combustion spud guns due to the increased variation possible in the components. Typical ranges are slightly higher because of the greater power, but the maximum range of some high power pneumatic cannons has been said to be over 1,000 metres (1,100 yd).

Pneumatic spud guns are generally more powerful than combustion spud guns. A typical combustion gun generates average chamber pressures of about 30 psi (210 kPa) with peaks of around 70–100 psi (500–700 kPa), while the average pneumatic gun can operate at pressures in the vicinity of 100 psi (700 kPa). In recent times, it has become increasingly common for metal pneumatic launchers to use even higher pressures, sometimes up to 500 psi (3.4 MPa) or higher

## Dry ice launchers

PVC dry ice cannon in use, 1.5kg (3 pounds) of concrete is poured at the bottom to reinforce it, and plastic sleeves are used to stiffen the lower (highest pressure) part.

A dry ice cannon uses the sublimation of solid carbon dioxide to generate the gas pressure to propel a projectile.

The oldest examples simply involve dropping pieces of dry ice into a tube closed at one end and sealing the other end by jamming the projectile in. When the pressure of the carbon dioxide from the subliming dry ice builds high enough, the projectile will be blown out of the tube. The pressures of such devices are not very high as it only needs to build enough to overcome the friction of the projectile jammed in the barrel. Tens of psi is most likely.

A more modern example is the dry ice bomb launcher. A plastic bottle containing water has some dry ice added and is quickly sealed and dropped down a tube closed at one end. A projectile is inserted in after it. The water accelerates the sublimation of the dry ice and the pressure from the carbon dioxide gas produced eventually ruptures the plastic bottle and launches the projectile. The rupturing pressure of a standard plastic soda bottle is between 200 and 300 psi (1.4 and 2.1 MPa) in the open air but when confined in a pipe, it could be higher.

Due to the operation of a dry ice bomb cannon extra safety issues are present:

- The dry ice bomb used for propulsion can achieve bursting pressure in a matter of seconds to hours depending on the quantity of water and dry ice. If too little dry ice, it also may not achieve bursting pressure at all. These timing issues can cause belief that the cannon has failed to fire but attempting to unload the cannon may then provide the extra stress on the bottle needed for it to rupture.
- Piping and any reinforcement of such may be underestimating the high pressure spike when the dry ice bomb explodes and plastic tubing may rupture with such forces
- The recoil of such cannons can be very great due to the high pressure combined with the large internal diameter piping needed for the bottles (5–9 cm; 2–3½ in) resulting in them being ill-suited for hand held firing.

Compared to the operation of other spud guns, dry ice bomb cannons are similar in firing principle to a burst disk cannon of the pneumatic type; the plastic bottle performing the task of the burst disk albeit in a less controlled manner.

Another means of utilising dry ice in spud guns is to use the sublimation of dry ice to create substantial pressure behind a valve, and placing a barrel on the other side of that valve with a projectile loaded into it. Pressures behind the valve can reach upwards of 800 psi (5.5 MPa), and by quickly releasing the valve, the projectile can be launched. Whilst this method is more controllable and in many means safer than utilising a soda bottle as a burst disk (provided pressure rated valves and piping are used), it is limited in that quick release valves, such as ball valves, are generally not bigger in diameter than 1 or 2 inches. Additionally, they cannont be opened as rapidly as a soda bottle will rupture, and consequently there is less immediate airflow. However, this is offset by the fact that such a design can operate at more than double the pressure of a typical dry ice bomb launcher, as soda bottles will rupture at only 200–300 psi (1.4–2.1 MPa).

### Hybrid launchers

A hybrid launcher consists of seven basic elements:

- A fuel system (usually metered propane)
- An air filling valve
- One or more pressure gauges
- A high pressure combustion chamber
- A pressure-triggered main valve (burst disk)
- A barrel
- An ignition source

A hybrid combines principles of the combustion and pneumatic spud gun. It uses a pre-pressurised mixture of fuel and air to get more power out of a given chamber volume.

In order to fire, the operator first readies the pressure-triggered valve then injects several times the normal amount of fuel and appropriately more air. When the ignition source is triggered, the pressure from the combustion causes the main valve to open and propels the projectile out of the barrel with the released combustion gases. The hybrid is capable of higher velocities than a combustion or pneumatic spud gun because the pressure generated is higher than that in a combustion gun (for most fuels), and the shock wave moves faster than it can in a pneumatic (for most gases), due to the higher temperature. Projectiles fired by a hybrid have broken the sound barrier.

A hybrid using a fuel and air mix at twice atmospheric pressure is said to be using a 2X mix. Higher mixtures can be used and will produce even higher pressures. The fuel and air needs to be measured and matched carefully to ensure reliable operation; hence the use of accurate air pressure gauges and fuel meters.

## *Primary materials*

### Plastics

- PVC-U (Polyvinyl chloride, unplasticized) - Highly popular due to its availability and relatively low cost. PVC pipes are available in a wide variety of sizes and pressure ratings. In industry, however, they are illegal for compressed air applications—if they are damaged under pressure the plastic can fail explosively.

- ABS (Acrylonitrile butadiene styrene) - Another popular plastic piping material, more expensive and less common than PVC but available in the same sizes and pressure ratings. Unlike PVC it is used in compressed air systems as it splits rather than shatters on failure. It also has a greater temperature tolerance (−40 °C to +80 °C, or −40 to 175 °F) compared to 0 °C to +60 °C or 30 to 140 °F for PVC).

Both PVC and ABS piping are also available in forms which are not pressure rated. Use of unrated plastic piping and fittings is a common source of cannon failure and poses a much greater risk to a cannon operator.

### Metals

- Steel - The very high pressure rating of steel piping makes it a familiar sight on high-powered hybrid cannons. It is however much more expensive than any other common piping material. The extra weight and joining difficulties are also a consideration.
- Copper - As a common plumbing material, copper pipes and associated fittings are readily available. They have higher pressure ratings and flow compared to similar plastic piping. The drawbacks are that copper is heavier, and up to four times the cost of PVC or ABS pipes of similar external diameters.
- Aluminium - Aluminium is a lightweight metal with good corrosion resistance. Aluminium pipes are sometimes used as barrels on spud guns on their own and machined aluminium is a popular material for particularly unique designs.
- Brass - Often brass fittings are used on spud guns for small parts of the construction like fuel systems, because it is one of the most common materials for small pipe fittings. Occasionally large parts of spud guns are machined entirely out of brass.

## *Valve types*

### Manual

- Ball Valve - Made out of either plastic or metal, ball valves are considered inferior by many enthusiasts due to their slow opening times. For those on a tight budget or in low-power setups, ball valves are ideal. Some choose to modify their valves by attaching a pneumatic actuator or spring to achieve a faster opening speed.
- Blowgun - A blowgun is a small hand held device used to blow away debris from a work area and is designed to be used attached to a compressed air line. It uses a sprung poppet valve operated by a lever to allow air through its body and out through a specially shaped nozzle. In spudgunning it is used to pilot larger valves - releasing a small volume of air to allow a piston or diaphragm to fly back and release a much larger volume of air into the barrel. It is also used as the primary valve for small cannons which fire airsoft pellets and so do not require high air flow. Blowguns can be modified to increase airflow.

## Electronic

- Sprinkler valve (otherwise known as a solenoid valve) - The use of irrigation sprinkler valves as pneumatic valves has become increasingly popular for spudgunning. These valves are intended to be electronically triggered causing a solenoid to depressurise a diaphragm and allow airflow through. It is also possible to remove the solenoid and, instead, to actuate the valve manually with a blowgun to depressurise the diaphragm. Such modifications allow the valve to open as much as 3 to 5 times faster.

## Pneumatic

- Diaphragm valve - A diaphragm valve is used in pneumatic cannons where the barrel is within the air chamber. It is a disk of flexible material mounted directly behind the barrel that seals it when pressure is increased behind the disk. The design is such that air leaks past the diaphragm from behind it to the chamber around the barrel, sealing the soft rubber against the butt of the barrel. Once the chamber is fully pressurised the compressed air behind the diaphragm is quickly vented, causing the centre of the diaphragm to flex backwards, exposing the butt of the barrel to the compressed air inside the chamber, which rapidly exhausts through the barrel, launching the projectile.
- Piston valve - The gold standard of pneumatic spudgunning is the piston valve, due to its extremely high rate of flow and opening speed. It works in an almost identical fashion to a diaphragm valve but replaces the flexible diaphragm with a hard rubber-faced piston. The valve opening is generally as wide as or wider than the barrel diameter, so there is very little constriction of airflow. Piston valves also open much faster than either ball or solenoid valves. However, construction of this type of valve is inherently complex, and some choose to order pre-built valves through the internet.
- Quick Exhaust Valve (QEV) - a commercial piston or diaphragm valve in a metal body intended for the quick venting of pneumatic cylinders. In spudgunning they are ideal barrel sealing valves with faster opening times than custom piston valves and high flow rates. They can be commonly found in sizes from ⅛ inch to 1½ inches (3–40 mm) and sometimes even larger models. It provides an easy option for inexperienced spud-gun builders but the cost is usually greater than for any other valve type.
- Burst Disk Valve - Used in a few pneumatics but primarily in hybrid cannons, burst valves are considered the ideal pressure release mechanism as they allow an unobstructed flow of high pressure air. Burst disks have no moving parts, making them very reliable. They are very appealing for hybrid cannons because they can withstand the low pressure gas mix in the chamber before ignition, yet fail as planned upon successful ignition. The high pressure combustion gases are released into the barrel at a rate which generates greater velocities than a mechanical valve could allow. Pneumatic cannon burst discs work similarly. The disc and projectile are loaded, and the chamber is pressurised until the disc ruptures. Unfortunately, this usually does not give the operators much in the way

of control over timing, although a puncturing mechanism can be used. Burst disks are of no specific material and may consist of plastic or thin sheet metal or foil.

- The Quick Dump Valve is a recent addition to the choices of valves for spudding. A QDV is a spool valve that is balanced under pressure with one end of the spool oriented toward the barrel. The spool is manually unbalanced allowing pressure between the end of the spool and the projectile in the barrel. The air pressure then forces the spool back and the projectile forward. Since the valve is triggered with no pilot pressure, the valve snaps open with no pilot pressure to hinder it. Currently it is not commercially for sale and must be hand built by the hobbyist like most piston valves.

## *Connections*

### Welding, soldering and gluing

- Solvent welding - used for similar plastic connections using solvent fittings, the solvent temporarily dissolves the polymer chains of the plastic and the parts to be joined are brought together. On rehardening, the polymer chains from each part are entangled and so form a solid weld.
- Metal welding - used to form strong joints between similar metals by melting the points of connection together. It is an uncommon process in spudgun construction due to the equipment necessary to make the welds.
- Soldering - commonly used in the construction of copper pipe based spudguns, a solder with a lower melting point than the copper is melted and drawn into the gaps between pipe and fitting with capillary action, holding to pipe and fitting with a wetting action before hardening.
- Gluing - the use of epoxy resin in small designs is common for the making of custom parts but it is rare to see glues used for structural connections.
- Duct tape - sometimes used in simple cannons, is unsuitable for sealing any significant pneumatic pressure and if used on a combustion cannon the heat produced can soften the glue and melt the tape, greatly weakening any seal or join it creates.

### Mechanical joints

- Compression Fittings - primarily seen on copper pipe spudguns, the compression fitting squeezes a metal ring against the pipe between a nut and the fitting body to form the connection. Easier than solder fittings and requiring only a spanner they are much more expensive and are of greater weight.
- Threaded Fittings - commonly available in BSP or NPT (not interchangeable) they generally require a fitting attached to a pipe by other means to allow screwing into another threaded fitting. The exception to this is steel pipe, the ends of which can have the appropriate thread cut into them.
- Flange joints - on large steel spudguns, pipe and fittings are sometimes bolted together by means of flanges with a gasket sandwiched between them to provide an airtight joint.

- Cam Locks - on spudguns with interchangeable barrels a cam lock is sometimes used to connect barrels to the cannon as it provides a quick and simple solution to switching barrels. Two levers either side of the socket side of the fitting rotate internal cams to lock in or release the plug side of the fitting to which a barrel is attached.

## The sound barrier

It is rare for a spud gun to be powerful enough to break the sound barrier, although there are some cases of this happening using specialized designs. The spud guns used are typically hybrids; but some pneumatic cannons have achieved the feat, either by using a special low density gas, such as helium, or high pressures combined with a fast valve. There is also one reported case of a combustion design achieving super-sonic velocities.

The difficulty in breaking the barrier arises from the speed of the particles within the gas. If the projectile is travelling at, or near to that speed, then the gases simply cannot keep up with it to provide the accelerating force. The problem is solved by increasing the speed of the particles, either by:

- Using lighter molecules, as occurs when helium is used in a pneumatic.
- Heating the gases to far higher temperatures, and thus giving them more energy. This allows hybrids and combustions to achieve supersonic velocities.
- Using steel and much higher pressures of 800 psi (5.5 MPa) or more, but achieving these pressures is difficult. $CO_2$ gas, although it can reach these pressures, is not suitable due to its high density.

Supersonic velocities may theoretically be attained by pneumatics with a sufficiently large "dead space" between the main valve and projectile. The incoming air can raise the pressure rapidly in this dead space, creating high temperatures sometimes sufficient to achieve supersonic velocities. This particular effect has not yet been successfully used, but has been discussed, as both adiabatic and shock heating are documented phenomenons in gases.

The highest projectile speed recorded from a spud gun is 933.3 m/s (3,062 ft/s) (approximately 2.7 times the speed of sound) with a 16.6-gram (256 gr) 20 mm plastic slug from a hybrid using a 1 MPa (150 psi) pre-ignition mixture of air and propane. The highest velocity attained by a potato specifically is approximately 2,700 ft/s (820 m/s).

## Practical uses

Although spudguns are created and used for the purpose of recreation there are other devices which work on identical principles in many other fields with more serious uses.

## Entertainment

- Promotional sports cannons: Portable pneumatic cannons which run on bottled $CO_2$ are common at large sports games in the U.S. where they are used to project items such as T-shirts or wrapped food into the audience. They tend to be made of higher quality materials than an average pneumatic spudgun but they use the same methods of operation.
- Special effects cannons: In film and theatre productions pneumatic cannons are often used as a pyrotechnic-free method of material projection. These can vary from simple ball valve, manually operated models to electronically triggered designs operated from a remote control panel depending on the exact requirements.

## Industry

A typical propane gun bird scarer.

- Hail cannons: these are very large devices which consist of a combustion chamber and a large funnel shape mounted on top of it. A gas mix is ignited in the combustion chamber and the funnel directs the blast wave upwards. They are intended to protect crops from hail damage by disrupting hail formation with the shock waves. There has however been no scientific proof of their effectiveness.
- Air cannons: This can mean:
    - A pneumatic spudgun

    - Air blaster, a compressed air device to unblock clogging in large storage containers (e.g. silos) for powdery material.
    - Air cannon (mechanics), a compressed air device for creating high pressure shock waves under water
- Bird scarers: these devices are essentially automatic combustion cannons. They require bottled propane gas and a lead-acid battery. At intervals they ignite a propane/air mix to produce a loud explosion (up to 150 decibels close to the device) to scare birds from crop fields or near airport runways.
- Chicken cannons: Many aircraft parts must be able to survive the impact of a bird in flight, known as a birdstrike. Pneumatic guns are used to project a bird, typically a dead chicken, into a product designed to mitigate a birdstrike. Aircraft canopies, engines, and critical flight control surfaces will normally undergo this type of stress testing to determine whether they are strong enough to withstand a birdstrike in flight.

### Military

- Combustion light gas guns are weaponised combustion cannons which burn a low molecular weight gas such as hydrogen to provide a higher specific impulse than relatively high molecular weight conventional solid propellants.

## *Safety*

Spud guns by nature are hazardous and can present safety issues if poorly constructed or used.

Users should follow the same rules as if handling a conventional firearm, but given the frequently improvised materials and construction used in spudguns, it is particularly important for the user to use basic ear and eye protection when operating a spudgun.

## *Legal issues*

In some jurisdictions spud guns are outlawed or have restrictions on their use and may require licenses and certification of the gun.

# Chapter 16

# Pneumatic Tube

Modern day Pneumatic tube terminal used in factories, supermarkets, banks/credit unions and medical facilities

**Pneumatic tubes** (or **capsule pipelines** or **Lamson tubes**; also known as **Pneumatic Tube Transport** or **PTT**) are systems in which cylindrical containers are propelled through a network of tubes by compressed air or by partial vacuum. They are used for transporting solid objects, as opposed to conventional pipelines, which transport fluids. Pneumatic tube networks gained great prominence in the late 19th and early 20th century for businesses or administrations that needed to transport small but urgent packages (such as mail or money) over relatively short distances (within a building, or, at most, within a city). Some of these systems grew to great complexity, but they were eventually superseded by more modern methods of communication and courier transport, and are now much rarer than before. However, in some settings, such as hospitals, they remain of great use, and have been extended and developed further technologically in recent decades.

A small number of pneumatic transportation systems were also built for larger cargo, to compete with more standard train and subway systems. However, these never gained as much popularity as practical systems.

## *History*

### Historical use

Pneumatics can be traced back to Hero of Alexandria in the 1st century AD, though there was apparently no thought of using them to move objects through pipes.

Pneumatic capsule transportation was originally invented by William Murdoch. Though a marvel of the time, and a successful sideshow, it was considered little more than a novelty until the invention of the capsule in 1836. The Victorians were the first to use *capsule pipelines* to transmit telegraph messages, or telegrams, to nearby buildings from telegraph stations.

While they are commonly used for small parcels and documents — now most often used as cash carriers at banks or supermarkets — they were originally proposed in the early 19th century for transport of heavy freight. It was once envisioned that networks of these massive tubes might be used to transport people.

**Current use**

NASA Mission Control Center during the Apollo 13 mission. Note pneumatic tube canisters in console to the right.

Pneumatic tubes in use at a drive-through bank.

The technology is still used on a smaller scale. While its use for communicating information has been completely superseded by electronic systems, pneumatic tubes are still widely used for transporting small valuable objects, or where convenience and speed in a local environment is useful.

In the United States, a large number of drive-up banks use pneumatic tubes to transport cash and documents between cars and tellers. Most hospitals have a computer-controlled pneumatic tube system to deliver drugs, documents and specimens to and from laboratories and nurses' stations. Many factories use them to deliver parts quickly across large campuses. Many larger stores use systems to securely transport excess cash from checkout stands to back offices, and to send change back to cashiers. NASA's original

Mission Control Center in Houston, Texas had pneumatic tubes connecting controller consoles with staff support rooms. Denver International Airport is noteworthy for the large number of pneumatic tube systems, including a 25 cm diameter system for moving aircraft parts to remote concourses, a 10 cm system for United Airlines ticketing, and a robust system in the parking toll collection system with an outlet at every booth.

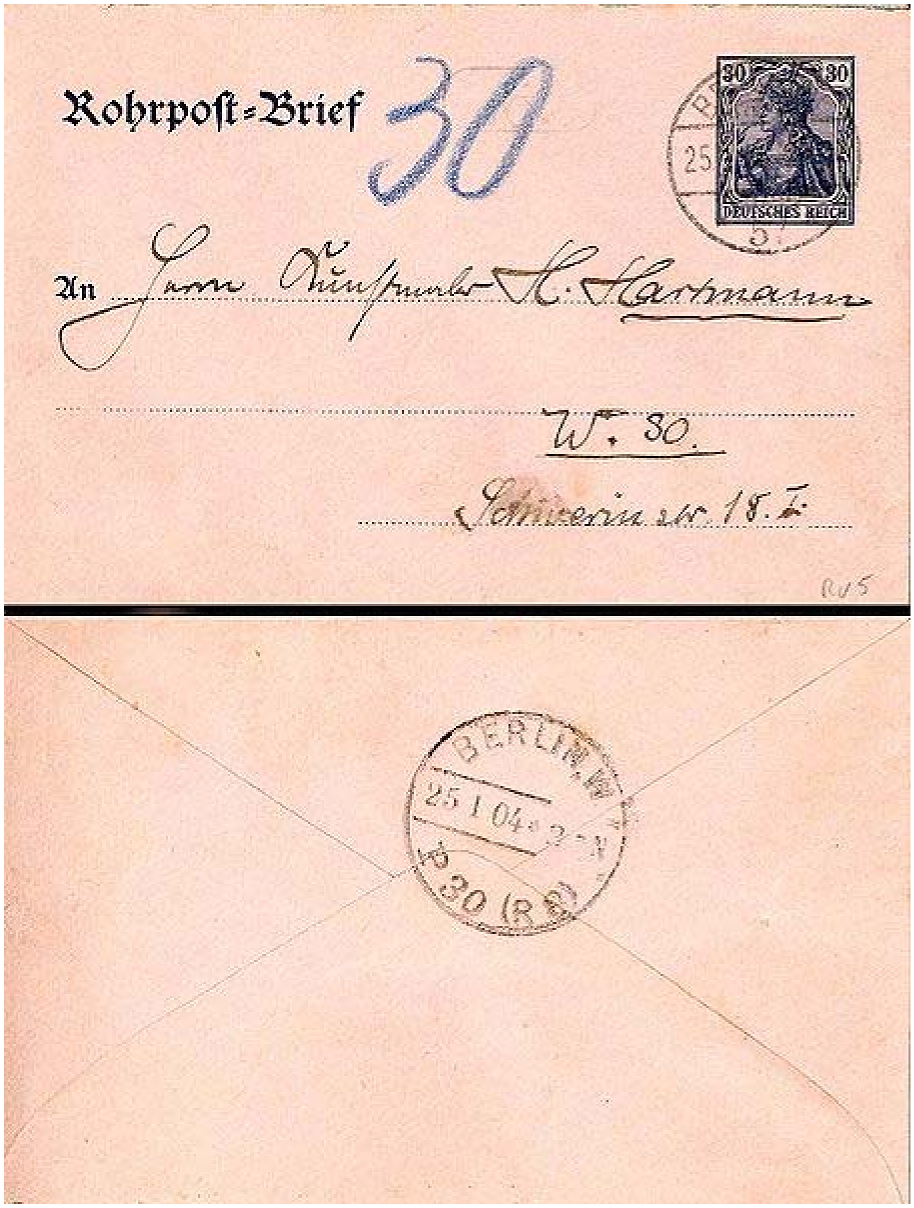
Pneumatic tube systems are used in science, to transport samples during neutron activation analysis. Samples must be moved from the nuclear reactor core, in which they are bombarded with neutrons, to the instrument that records the resulting radiation. As some of the radioactive isotopes in the sample can have very short half-lives, speed is important. These systems may be automated, with a magazine of sample tubes that are moved into the reactor core in turn for a predetermined time, before being moved to the instrument station and finally to a container for storage and disposal.

Until it closed in early 2011, a McDonald's in Edina, MN claimed on its receipts to be the "World's Only Pneumatic Air Drive-Thru," sending food from their strip-mall location to a drive-through in the middle of a parking lot.

In Britain, the House of Commons telephone and computer exchange also has a pneumatic tube system in place.

### *Usages*

### In postal service




Pneumatic tube letter from Berlin, Germany, 1904

**Pneumatic post** or **pneumatic mail** is a system to deliver letters through pressurized air tubes. It was invented by the Scottish engineer William Murdoch in the 19th century and was later developed by the London Pneumatic Despatch Company. Pneumatic post systems were used in several large cities starting in the second half of the 19th century (including an 1866 London system powerful and large enough to transport humans during trial runs - though not intended for the purpose), but were largely abandoned during the 20th century.

It was also speculated that a system of tubes might deliver mail to every home in the US. A major network of tubes in Paris was in use until 1984, when it was finally abandoned in favor of computers and fax machines. In Prague, in the Czech Republic, a network of tubes extending approximately 60 kilometres in length still exists for delivering mail and parcels. Following the 2002 European floods, the Prague system sustained damage, and operation was mothballed indefinitely.

Pneumatic post stations usually connected post offices, stock exchanges, banks and ministries. Italy was the only country to issue postage stamps (between 1913 and 1966) specifically for pneumatic post. Austria, France, and Germany issued postal stationery for pneumatic use.

Typical current applications are in banks and hospitals. Many large retailers use pneumatic tubes to transport cheques or other documents from cashiers to the accounting office.

Historical use

- 1853: linking the London Stock Exchange to the city's main telegraph station (a distance of 220 yards)
- 1861: in London with the London Pneumatic Despatch Company providing services from Euston railway station to the General Post Office and Holborn
- 1865: in Berlin (until 1976), the *Rohrpost*, a system 400 kilometers in total length at its peak in 1940
- 1866: in Paris (until 1984, 467 kilometers in total length from 1934)
- 1875: in Vienna (until 1956)
- 1887: in Prague (until 2002 due to flooding), the Prague pneumatic post
- 1897: in New York City (until 1953)
- other cities: Munich, Rio de Janeiro, Buenos Aires, Hamburg, Rome, Naples, Milan, Marseilles, Melbourne, Boston, Philadelphia, Chicago, St. Louis

## In public transportation

19th century

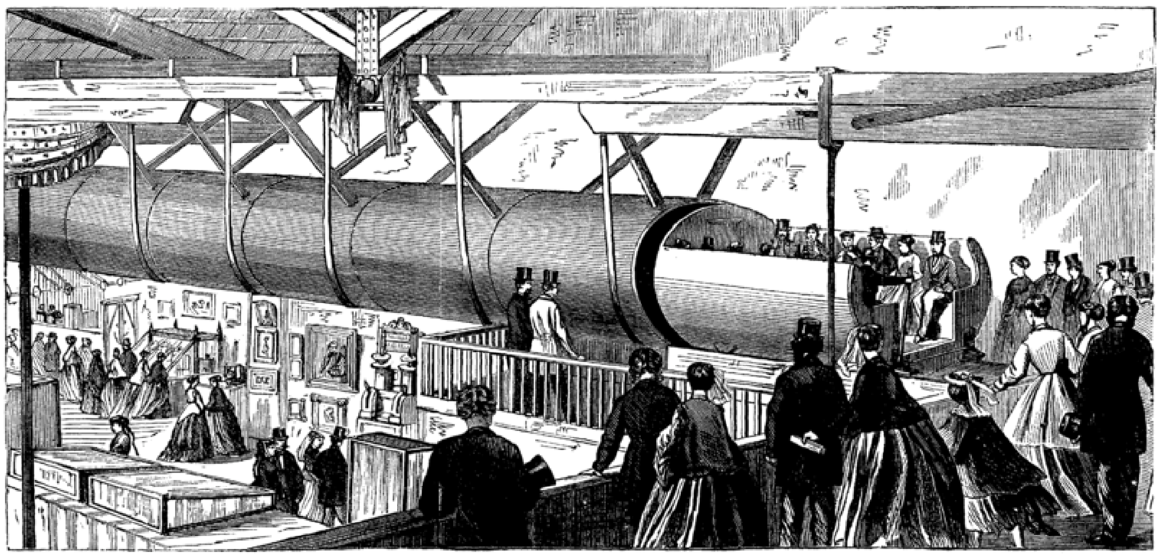
In 1812, George Medhurst first proposed, but never implemented, blowing passenger carriages through a tunnel. Precursors of pneumatic tube systems for passenger transport, the atmospheric railway (for which the tube was laid between the rails, with a piston running in it suspended from the train through a sealable slot in the top of the tube) were operated as follows:

- 1844–54: Dublin and Kingstown Railway's Dalkey Atmospheric Railway between Kingstown (Dún Laoghaire) and Dalkey, Ireland (1.75 mi (3 km))
- 1846–47: London and Croydon Railway between Croydon and New Cross, London, England (7.5 mi (12 km))
- 1847–48: Isambard Kingdom Brunel's South Devon Railway between Exeter and Newton Abbot, England (20 mi (32 km))

- 1847–60: Paris–Saint-Germain railway between Bois de Vésinet and Saint-Germain-en-Laye, France (2 km (1 mi))

In 1861, the **London Pneumatic Despatch Company** built a system large enough to move a person, although it was intended for parcels. The inauguration of the new Holborn Station on 10 October 1865 was marked by having the Duke of Buckingham, the chairman, and some of the directors of the company blown through the tube to Euston (a five minute trip).

The 550-meter Crystal Palace pneumatic railway was exhibited at the Crystal Palace in 1864. This was a prototype for a proposed *Waterloo and Whitehall Railway* that would have run under the River Thames linking Waterloo and Charing Cross. Digging commenced in 1865 but was halted in 1868 due to financial problems.



Alfred Ely Beach's experimental pneumatic elevated subway on display in 1867

In 1867 at the American Institute Fair in New York, Alfred Ely Beach demonstrated a 32.6 m long, 1.8 m diameter pipe that was capable of moving 12 passengers plus a conductor. In 1869, the Beach Pneumatic Transit Company of New York secretly constructed a 95 m long, 2.7 m diameter pneumatic subway line under Broadway, to demonstrate the possibilities of the new transport mode. The line only operated for a few months, closing after Beach was unsuccessful in getting permission to extend it – Boss Tweed, an immensely powerful local politician, did not want it to go ahead as he was intending to personally invest into competing schemes for an elevated rail line.

20th century

In the 1960s, Lockheed and MIT with the United States Department of Commerce conducted feasibility studies on a vactrain system powered by ambient atmospheric pressure and "gravitational pendulum assist" to connect cities on the East Coast of the US. They calculated that the run between Philadelphia and New York City would average

174 meters per second, that is 626 km/h (388 mph). When those plans were abandoned as too expensive, Lockheed engineer L.K. Edwards founded Tube Transit, Inc. to develop technology based on "gravity-vacuum transportation". In 1967 he proposed a **Bay Area Gravity-Vacuum Transit** for California that would run alongside the then-under construction BART system. It was never built.

21st century

Research into trains running in partially-evacuated tubes is continuing.

## *Technical characteristics*

Modern systems (for smaller, i.e. "normal" tube diameters as used in the transport of small capsules) reach speeds of around 7.5 m (25 ft) per second, though some historical systems already achieved speeds of 10 m (33 ft) per second. Further, modern systems can also be computer-controlled, allowing, among other things, the tracking of any specific capsule. Varying air pressures also allow capsules to brake slowly, removing the jarring arrival that used to characterise earlier systems and make them unsuitable for fragile contents.

## Chapter 17

# Pneumatic Tool and Nail Gun

# Pneumatic tool

*Pneumatic tools'* or **air tools** are tools driven by gas, usually compressed air supplied by a gas compressor. Pneumatic tools can also be driven by compressed carbon dioxide ($CO_2$) stored in small cylinders allowing for portability. Pneumatic tools are commonly cheaper and safer to run and maintain than their electric power tool counterparts, as well as having a higher power to weight ratio, allowing a smaller, lighter tool to accomplish the same task.

Air tools were formerly unpopular in the DIY market, but are becoming increasingly popular, and have always been ubiquitous in industrial and manufacturing settings.

Flow represents the quantity of compressed air that passes through a section over a unit of time. It is represented in l/min, m3, at the equivalent value in free air in conditions of standard reference atmosphere (SRA), i.e. +20 c, 65% of relative humidity, 1013 mbar, in accordance with norms NFE

### *Some common pneumatic tools*

- Air impact wrench
- Air ratchet
- Airbrush
- Jackhammer
- pneumatic grinder
- pneumatic sander
- Pneumatic drill
- pneumatic screwdriver
- pneumatic tapping machine
- pneumatic hack saw
- Pneumatic Hammers (Stone Sculpting)
- pneumatic trimmer

- pneumatic paint gun
- pneumatic tacker
- pneumatic polisher
- pneumatic nail gun
- sandblaster
- Paint sprayer

### *Some common brand names*

- Cuturi Martelli Pneumatici
- Bavaria Lufthammer
- Milani (Toncani) Martelli Pneumatici / Utensili
- RAD Torque Systems
- RAD Torque Systems
- RAD Torque Systems
- Fuji Air Tools Co.,LTD
- Dynabrade
- Ober Spa
- 3M
- Atlas Copco
- Compair Broomwade Ltd
- Ingersoll-Rand
- Snap-on
- Chicago Pneumatic
- Master Air Tool
- ELGI
- Bostich
- KAESER

In addition, many house brands exist, such as those carried at Princess Auto, Summit Tools or Harbor Freight Tools.

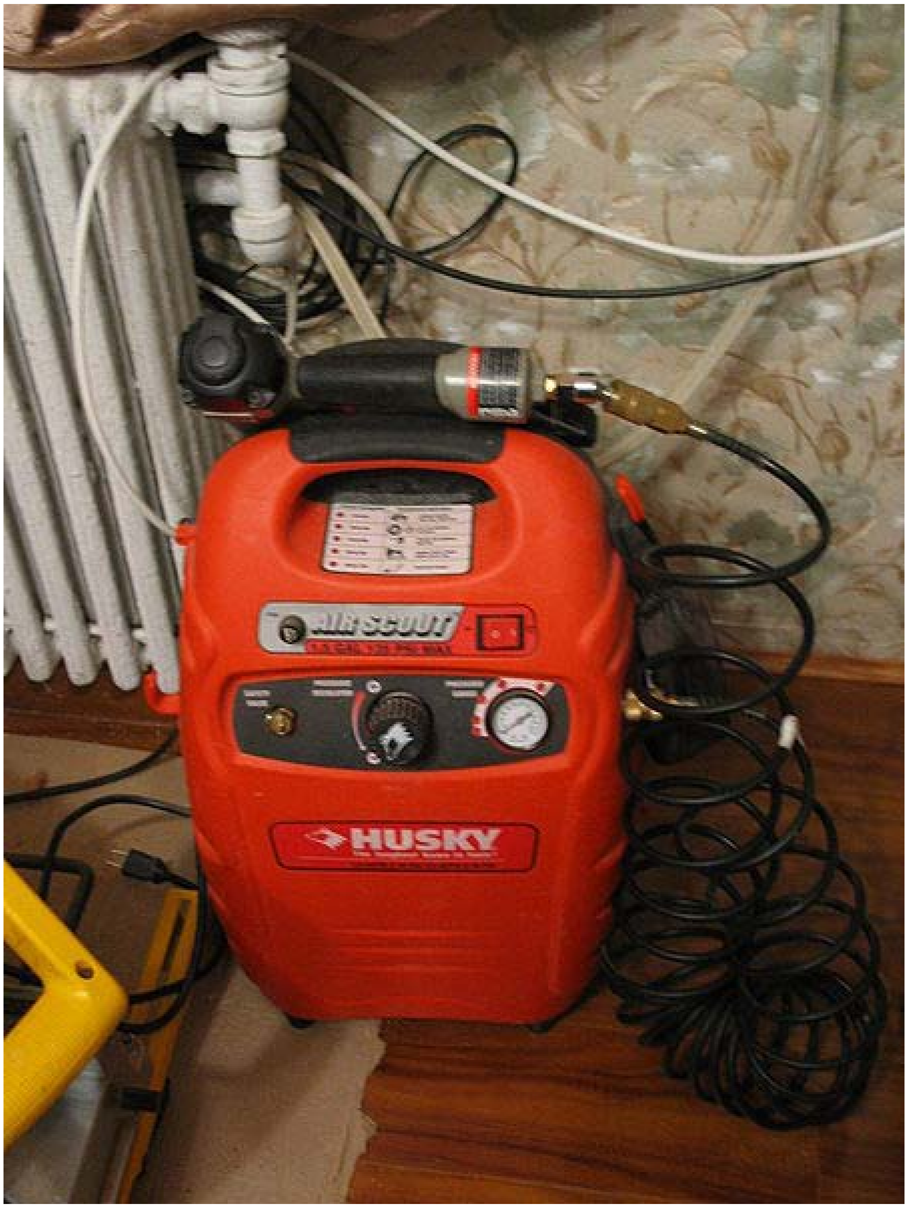
# Nail gun


Pneumatic nail gun in use

A **nail gun**, **nailgun** or **nailer** is a type of tool used to drive nails into wood or some other kind of material. It is usually driven by electromagnetism, compressed air (pneumatic), highly flammable gases such as butane or propane, or, for powder-actuated tools, a small explosive charge. Nail guns have in many ways replaced hammers as tools of choice among builders.

## *Usage*

Nail guns do not use individual fasteners. Instead, the fasteners are mounted in long strips (similar to a stick of staples) or collated in a paper or plastic carrier, depending on the design of the nailgun. Some full head nail guns, especially those used for pallet making and roofing, use long plastic or wire collated coils. Some strip nailers use a clipped head so the nails can be placed closer together, which necessitates less frequent reloading. Industrial nailers designed for use against steel or concrete may have a self-loading action for the explosive caps, but most require nails to be loaded by hand. Nail guns vary in the length and gauge (thickness) of nails they can drive.




Air compressor supplies air into a nail gun

The smallest size of fasteners are normally 24 to 22 gauge (0.60 to 0.71 mm diameter) and generally have no head. They are used for attaching beadings, mouldings and so forth to furniture, etc. Lengths are normally in the range ⅜ to 1¼ in. (10 to 32 mm) although some specialist manufacturers supply up to 2 in. (50 mm)

The next size up is the 18 gauge (1.22 mm diameter) fixing, often referred to as a "brad nail". These fastenings are also used to fix mouldings but can be used in the same way as the smaller 22 to 24 gauge fastenings. Their greater strength leads to their use in trim carpentry on hardwoods where some hole filling is acceptable. Whilst most 18 gauge brads have heads, some manufacturers do offer headless fastenings. Lengths range from ⅝ in to 2 in. (16 mm to 50 mm)

Going up from 18 gauge fastenings the next sizes are 16 and 15 gauge (1.63 and 1.83 mm diameter). These are generally referred to a "finish nails". They come in lengths between ⅝ and 2½ in. (16 to 64 mm) and are used in the general fixing of much softwood and MDF trim work (such as baseboard/skirtings, architraves, etc.) where the holes will be filled and the work painted afterwards.

The largest sizes of conventional collated fastenings are the clipped head and full head nails which are used in framing, fencing and other forms of structural and exterior work. These nails generally have a shank diameter of 0.11 to 0.13 in. (2.9 to 3.1 mm) although some manufacturers offer smaller diameter nails as well. General lengths are in the range 2 in to 3 ⅓ in (50 to 90 mm). Shank styles include plain, ring annular, twisted, etc. and a variety of materials and finishes are offered including plain steel, galvanised steel, sherardised steel, stainless steel, etc. depending on the pull-out resistance, corrosion resistance, etc. required for the given application. These sizes of fastenings are available in stick collated form (often 20° to 21° for full head, 28° to 34° for clipped head) or coil form (for use in pallet/roofing nailers) depending on the application. Full-head nails have greater pull-out resistance than clipped head nails and are mandated by code in many hurricane zones for structural framing.

Another type of fastening commonly found in construction is the strap fastening which is roughly analogous to the large head clout nail. These are used in conjunction with a strap shot nailer (or positive placement nailer *UK*) to fix metalwork such as joist hangers, corner plates, strengthening straps, etc. to timber structures. They differ from conventional nailers in that the point of the fastening is not sheathed so it can be exactly positioned before firing the nail gun.

Other specialist nailers are also available which can drive spikes up to 6¼ inches long, fix wood to steel, etc.

A variation on the nail gun is the palm nailer which is a lightweight handheld pneumatic nailer that straps to the hand. It is convenient for working in tight spaces where a conventional nailer will not fit and is flexible enough to drive either short nails into metal straps or six inch nails into timber. By repeated hammer action (of around 40 hits per second) the fastener is driven into the material by a more constant palm pressure (as opposed to a conventional nailgun which drives the nail against the inertia of the nailgun itself).

## Safety

In the United States, about 37,000 people every year go to emergency rooms with injuries from nail guns, according to the U.S. Centers for Disease Control (CDC). Forty percent of those injuries occur to consumers. Nail gun injuries tripled between 1991 to 2005. Foot and hand injuries are among the most common. The U.S. Consumer Product Safety Commission estimates that treating nail gun wounds costs at least $338 million per year nationally in emergency medical care, rehabilitation, and workers' compensation.

All kinds of nail guns can be dangerous, so safety precautions similar to those for a firearm are usually recommended for their use. For safety, nail guns are designed to be used with the muzzle touching the target. Unless specifically modified for the purpose, they are not effective as projectile weapons.

The most common firing mechanism is the dual-action contact-trip trigger, which requires that the manual trigger and nose contact element both be depressed for a nail to be discharged. The sequential-trip trigger, which is safer, requires the nose contact to be depressed before the manual trigger, rather than simultaneously with the trigger. Approximately 65% to 69% of injuries from contact-trip tools could be prevented through the use of a sequential-trip trigger, according to the CDC.

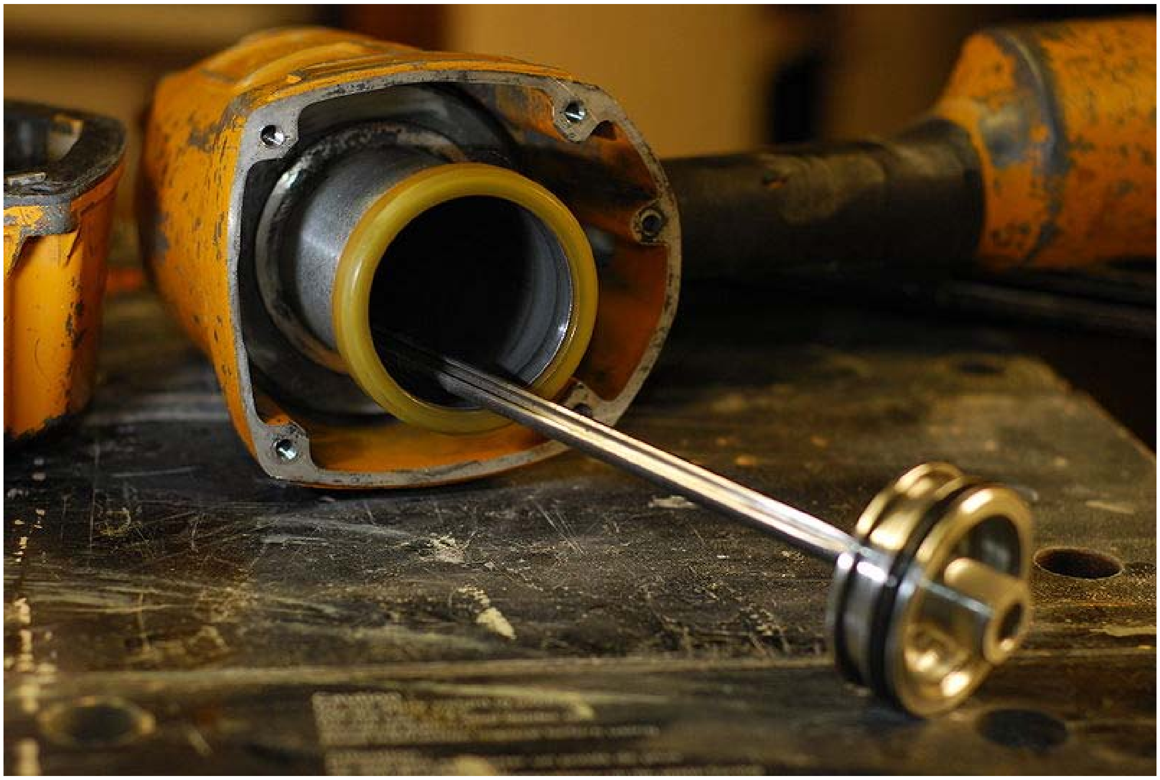
### *Powder actuation*

Explosive-powered ("powder actuated") nailguns fall into two broad categories:

- Direct drive or high velocity devices. This uses gas pressure acting directly on the nail to drive it.
- Indirect drive or low velocity devices. This uses gas pressure acting on a heavy piston which drives the nail. Indirect drive nailers are safer because they cannot launch a free-flying projectile even if tampered with or misused, and the lower velocity of the nails is less likely to cause explosive shattering of the work substrate.

Either type can, with the right cartridge loads, be very powerful, driving a nail or other fastener into hard concrete, stone, rolled steelwork, etc., with ease.


Pneumatic nail guns require air hoses to fire



In the nailgun's head, the inner chamber contains the piston assembly which drives the nail.


Nails come in clips for use in nail guns

Cartridges, used in powder actuated nail guns

## Chapter 18

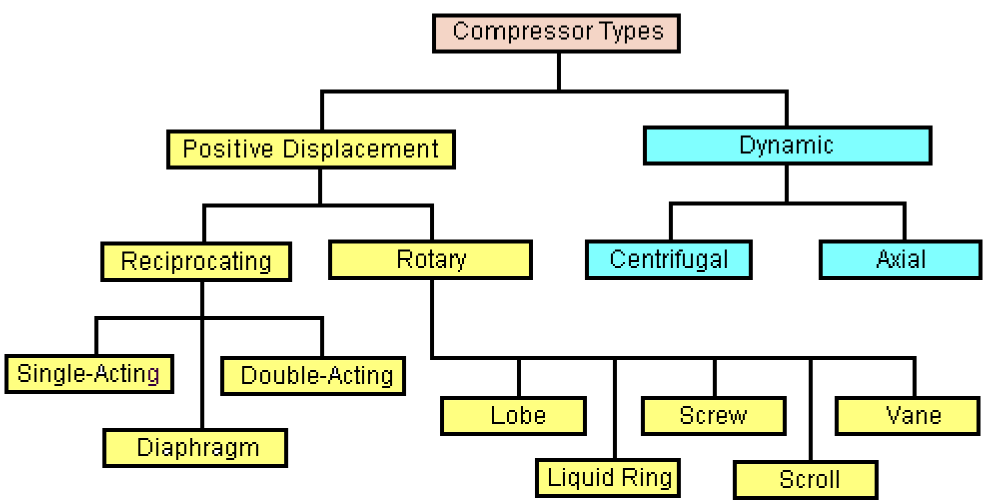
# Gas Compressor

A **gas compressor** is a mechanical device that increases the pressure of a gas by reducing its volume.

Compressors are similar to pumps: both increase the pressure on a fluid and both can transport the fluid through a pipe. As gases are compressible, the compressor also reduces the volume of a gas. Liquids are relatively incompressible, while some can be compressed, the main action of a pump is to pressurize and transport liquids.

### *Types of compressors*

The main types of gas compressors are illustrated and discussed below:



### Hermetically-Sealed, Open, or Semi-


A small hermetically sealed compressor in a common consumer refrigerator or freezer; it typically has a rounded steel outer shell that is permanently welded shut, and which seals operating gases inside the system. There is no route for gases to leak, such as around motor shaft seals. On this model, the plastic top section is part of an auto-defrost system which use motor heat to evaporate the water.

Compressors are often described as being either open, hermetic, or semi-hermetic, to describe how the compressor and motor drive is situated in relation to the gas or vapour being compressed. The industry name for a hermetic is **hermetically sealed compressor**, while a semi- is commonly called a **semi hermetic compressor**.

In hermetic and most semi-hermetic compressors, the compressor and motor driving the compressor are integrated, and operate within the pressurized gas envelope of the system. The motor is designed to operate and be cooled by the gas or vapour being compressed.

The difference between the hermetic and semi-hermetic, is that the hermetic uses a one-piece welded steel casing that cannot be opened for repair; if the hermetic fails it is simply replaced with an entire new unit. A semi-hermetic uses a large cast metal shell with gasketed covers that can be opened to replace motor and pump components.

The primary advantage of a hermetic and semi-hermetic is that there is no route for the gas to leak out of the system. Open compressors rely on either natural leather or synthetic rubber seals to retain the internal pressure, and these seals require a lubricant such as oil to retain their sealing properties.

An open pressurized system such as an automobile air conditioner can leak its operating gases, if it is not operated frequently enough. Open systems rely on lubricant in the system to splash on pump components and seals. If it is not operated frequently enough, the lubricant on the seals slowly evaporates, and then the seals begin to leak until the system is no longer functional and must be recharged. By comparison, a hermetic system can sit unused for years, and can usually be started up again at any time without requiring maintenance or experiencing any loss of system pressure.

The disadvantage of hermetic compressors is that the motor drive cannot be repaired or maintained, and the entire compressor must be removed if a motor fails. A further disadvantage is that burnt out windings can contaminate whole systems requiring the system to be entirely pumped down and the gas replaced. Typically hermetic compressors are used in low-cost factory-assembled consumer goods where the cost of repair is high compared to the value of the device, and it would be more economical to just purchase a new device.

An advantage of open compressors is that they can be driven by non-electric power sources, such as an internal combustion engine or turbine. However, open compressors that drive refrigeration systems are generally not totally *maintenance free* throughout the life of the system, since some gas leakage will occur over time.

## Centrifugal compressors

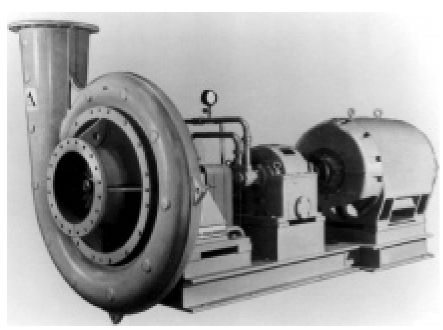


Figure 1: A single stage centrifugal compressor

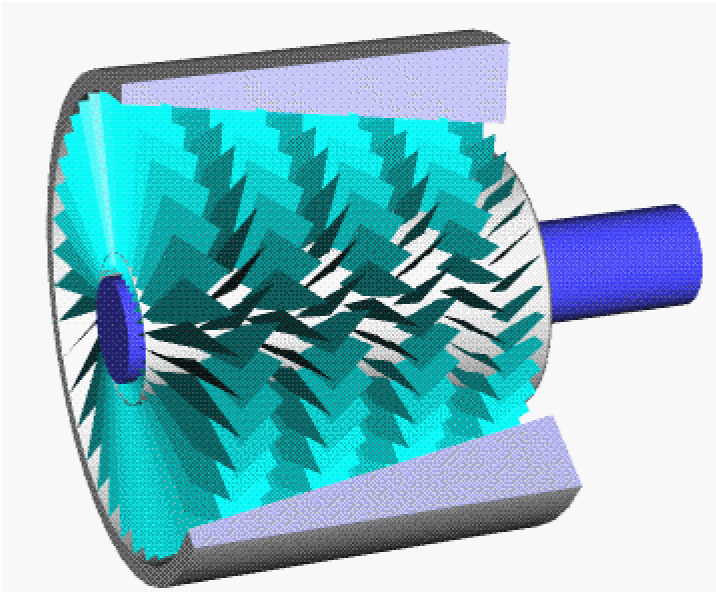
**Centrifugal compressors** use a rotating disk or impeller in a shaped housing to force the gas to the rim of the impeller, increasing the velocity of the gas. A diffuser (divergent duct) section converts the velocity energy to pressure energy. They are primarily used for continuous, stationary service in industries such as oil refineries, chemical and petrochemical plants and natural gas processing plants. Their application can be from 100 horsepower (75 kW) to thousands of horsepower. With multiple staging, they can achieve extremely high output pressures greater than 10,000 psi (69 MPa).

Many large snowmaking operations (like ski resorts) use this type of compressor. They are also used in internal combustion engines as superchargers and turbochargers. Centrifugal compressors are used in small gas turbine engines or as the final compression stage of medium sized gas turbines. Sometimes the capacity of the compressors is written in NM3/hr. Here 'N' stands for normal temperature pressure (20°C and 1 atm ) for example 5500 NM3/hr.

## Diagonal or mixed-flow compressors

**Diagonal** or **mixed-flow compressors** are similar to centrifugal compressors, but have a radial and axial velocity component at the exit from the rotor. The diffuser is often used to turn diagonal flow to an axial rather than radial direction.

## Axial-flow compressors



Axial compressor.

**Axial-flow compressors** are dynamic rotating compressors that use arrays of fan-like airfoils to progressively compress the working fluid. They are used where there is a requirement for a high flow rate or a compact design.

The arrays of airfoils are set in rows, usually as pairs: one rotating and one stationary. The rotating airfoils, also known as blades or *rotors*, accelerate the fluid. The stationary airfoils, also known as *stators* or vanes, decelerate and redirect the flow direction of the fluid, preparing it for the rotor blades of the next stage. Axial compressors are almost always multi-staged, with the cross-sectional area of the gas passage diminishing along the compressor to maintain an optimum axial Mach number. Beyond about 5 stages or a 4:1 design pressure ratio, variable geometry is normally used to improve operation.

Axial compressors can have high efficiencies; around 90% polytropic at their design conditions. However, they are relatively expensive, requiring a large number of components, tight tolerances and high quality materials. Axial-flow compressors can be found in medium to large gas turbine engines, in natural gas pumping stations, and within certain chemical plants.

## Reciprocating compressors

A motor-driven six-cylinder reciprocating compressor that can operate with two, four or six cylinders.

**Reciprocating compressors** use pistons driven by a crankshaft. They can be either stationary or portable, can be single or multi-staged, and can be driven by electric motors or internal combustion engines. Small reciprocating compressors from 5 to 30 horsepower (hp) are commonly seen in automotive applications and are typically for intermittent duty. Larger reciprocating compressors well over 1,000 hp (750 kW) are commonly found in large industrial and petroleum applications. Discharge pressures can range from low pressure to very high pressure (>18000 psi or 180 MPa). In certain applications, such as air compression, multi-stage double-acting compressors are said to be the most efficient compressors available, and are typically larger, and more costly than comparable rotary units. Another type of reciprocating compressor is the swash plate compressor, which uses pistons which are moved by a swash plate mounted on a shaft - see Axial Piston Pump.

Household, home workshop, and smaller job site compressors are typically reciprocating compressors 1½ hp or less with an attached receiver tank.

## Rotary screw compressors

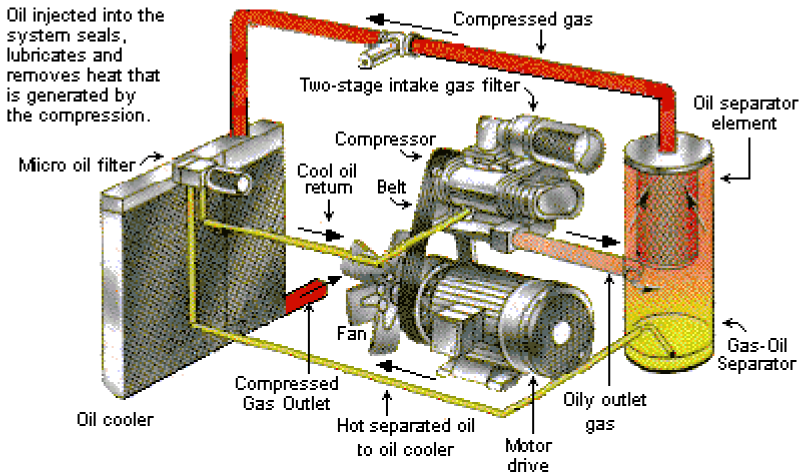



Diagram of a rotary screw compressor

**Rotary screw compressors** use two meshed rotating positive-displacement helical screws to force the gas into a smaller space. These are usually used for continuous operation in commercial and industrial applications and may be either stationary or portable. Their application can be from 3 horsepower (2.2 kW) to over 1,200 horsepower (890 kW) and from low pressure to moderately high pressure (>1,200 psi or 8.3 MPa).

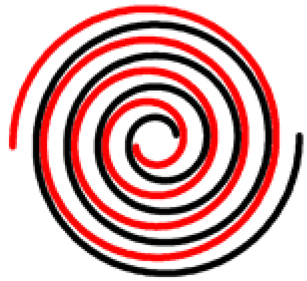
## Rotary vane compressors

**Rotary vane compressors** consist of a rotor with a number of blades inserted in radial slots in the rotor. The rotor is mounted offset in a larger housing which can be circular or a more complex shape. As the rotor turns, blades slide in and out of the slots keeping contact with the outer wall of the housing. Thus, a series of decreasing volumes is created by the rotating blades. Rotary Vane compressors are, with piston compressors one of the oldest of compressor technologies.

With suitable port connections, the devices may be either a compressor or a vacuum pump. They can be either stationary or portable, can be single or multi-staged, and can be driven by electric motors or internal combustion engines. Dry vane machines are used at relatively low pressures (e.g., 2 bar or 200 kPa; 29 psi) for bulk material movement while oil-injected machines have the necessary volumetric efficiency to achieve pressures up to about 13 bar (1,300 kPa; 190 psi) in a single stage. A rotary vane compressor is well suited to electric motor drive and is significantly quieter in operation than the equivalent piston compressor.

Rotary vane compressors can have mechanical efficiencies of about 90%.

## Scroll compressors



Mechanism of a scroll pump

A **scroll compressor**, also known as **scroll pump** and **scroll vacuum pump**, uses two interleaved spiral-like vanes to pump or compress fluids such as liquids and gases. The vane geometry may be involute, archimedean spiral, or hybrid curves. They operate more smoothly, quietly, and reliably than other types of compressors in the lower volume range

Often, one of the scrolls is fixed, while the other orbits eccentrically without rotating, thereby trapping and pumping or compressing pockets of fluid or gas between the scrolls.

This type of compressor was used as the supercharger on Volkswagen G60 and G40 engines in the early 1990s.

## Diaphragm compressors

A **diaphragm compressor** (also known as a **membrane compressor**) is a variant of the conventional reciprocating compressor. The compression of gas occurs by the movement of a flexible membrane, instead of an intake element. The back and forth movement of the membrane is driven by a rod and a crankshaft mechanism. Only the membrane and the compressor box come in contact with the gas being compressed.

Diaphragm compressors are used for hydrogen and compressed natural gas (CNG) as well as in a number of other applications.

A three-stage diaphragm compressor

The photograph included in this section depicts a three-stage diaphragm compressor used to compress hydrogen gas to 6,000 psi (41 MPa) for use in a prototype compressed hydrogen and compressed natural gas (CNG) fueling station built in downtown Phoenix, Arizona by the Arizona Public Service company (an electric utilities company). Reciprocating compressors were used to compress the natural gas.

The prototype alternative fueling station was built in compliance with all of the prevailing safety, environmental and building codes in Phoenix to demonstrate that such fueling stations could be built in urban areas.

### Air bubble compressor

A mixture of air and water generated through turbulence is allowed to fall into a subterranean chamber where the air separates from the water. The weight of falling water compresses the air in the top of the chamber. A submerged outlet from the chamber allows water to flow to the surface at a lower height than the intake. An outlet in the roof of the chamber supplies the compressed air to the surface. A facility on this principal was built on the Montreal River at Ragged Shutes neary Cobalt, Ontario in 1910 and supplied 5,000 horsepower to nearby mines.

## *Temperature*

Compression of a gas naturally increases its temperature, often referred to as the *heat of compression*. $W = \int_{V_1}^{V_2} P dV = P_1 V_1^n \int_{V_1}^{V_2} V^{-n} dV$ where

$$\frac{P_2}{P_1} = \left(\frac{v_1}{v_2}\right)^n$$

so

$$W = \frac{P_1 V_1^n}{1-n} \left(V_2^{1-n} - V_1^{1-n}\right)$$

with n taking different values for different compression processes.

- Adiabatic - This model assumes that no energy (heat) is transferred to or from the gas during the compression, and all supplied work is added to the internal energy of the gas, resulting in increases of temperature and pressure. Theoretical temperature rise is:

$T_2 = T_1 . {R_c}^{(k-1)/k}$ with $T_1$ and $T_2$ in degrees Rankine or kelvins, and $k$ = ratio of specific heats (approximately 1.4 for air). $R_c$ is the compression ratio; being the absolute outlet pressure divided by the absolute inlet pressure. The rise in air and temperature ratio means compression does not follow a simple pressure to volume ratio. This is less efficient, but quick. Adiabatic compression or expansion more closely model real life when a compressor has good insulation, a large gas volume, or a short time scale (i.e., a high power level). In practice there will always be a certain amount of heat flow out of the compressed gas. Thus, making a perfect adiabatic compressor would require perfect heat insulation of all parts of the machine. For example, even a bicycle tire pump's metal tube becomes hot as you compress the air to fill a tire. The relation between temperature and compression ratio described above means that the value of n for an adiabatic process is k (the ratio of specific heats).

- Isothermal - This model assumes that the compressed gas remains at a constant temperature throughout the compression or expansion process. In this cycle, internal energy is removed from the system as heat at the same rate that it is added by the mechanical work of compression. Isothermal compression or expansion more closely models real life when the compressor has a large heat exchanging surface, a small gas volume, or a long time scale (i.e., a small power level). Compressors that utilize inter-stage cooling between compression stages come closest to achieving perfect isothermal compression. However, with practical devices perfect isothermal compression is not attainable. For example, unless you have an infinite number of compression stages with corresponding intercoolers, you will never achieve perfect isothermal compression.

For an isothermal process, n is 1, so the value of the work integral for an isothermal process is:

$$W = -P_1 v_1 \ln\left(\frac{P_2}{P_1}\right)$$

When evaluated, the isothermal work is found to be lower than the adiabatic work.

- Polytropic - This model takes into account both a rise in temperature in the gas as well as some loss of energy (heat) to the compressor's components. This assumes that heat may enter or leave the system, and that input shaft work can appear as both increased pressure (usually useful work) and increased temperature above adiabatic (usually losses due to cycle efficiency). Compression efficiency is then the ratio of temperature rise at theoretical 100 percent (adiabatic) vs. actual (polytropic). Polytropic compression will use a value of n between 0 (a constant-pressure process) and infinity (a constant volume process). For the typical case where an effort is made to cool the gas compressed by an approximately adiabatic process, the value of n will be between 1 and k.

## *Staged compression*

In the case of centrifugal compressors, commercial designs currently do not exceed a compression ratio of more than a 3.5 to 1 in any one stage (for a typical gas). Since compression generates heat, the compressed gas is to be cooled between stages making the compression less adiabatic and more isothermal. The inter-stage coolers typically result in some partial condensation that is removed in vapor-liquid separators.

In the case of small reciprocating compressors, the compressor flywheel may drive a cooling fan that directs ambient air across the intercooler of a two or more stage compressor.

Because rotary screw compressors can make use of cooling lubricant to remove the heat of compression, they very often exceed a 9 to 1 compression ratio. For instance, in a typical diving compressor the air is compressed in three stages. If each stage has a compression ratio of 7 to 1, the compressor can output 343 times atmospheric pressure ($7 \times 7 \times 7 = 343$ atmospheres). (343 atm/34.8 MPa; 5.04 ksi)

## *Prime movers*

There are many options for the "prime mover" or motor which powers the compressor:

- gas turbines power the axial and centrifugal flow compressors that are part of jet engines
- steam turbines or water turbines are possible for large compressors
- electric motors are cheap and quiet for static compressors. Small motors suitable for domestic electrical supplies use single phase alternating current. Larger motors can only be used where an industrial electrical three phase alternating current supply is available.
- diesel engines or petrol engines are suitable for portable compressors and support compressors. Common in automobiles and other types of vehicles (including piston-powered airplanes, boats, trucks, etc.), diesel or gasoline engines can power compressors using their own crankshaft power (this setup known as a supercharger), or, using their waste exhaust gas to spin a turbine connected to the the compressor (this setup known as a turbocharger).

## *Multiple compressor configurations*

It is possible to connect two or more compressors in tandem, effectivly doubling their CFM output and air storage capacity. The advantages of such a configuration are portability and cost savings. It is significantly less expensive to purchase smaller compressors and rig them together than it would be to purchase one large compressor with the same output.

## *Applications*

Gas compressors are used in various applications where either higher pressures or lower volumes of gas are needed:

- in pipeline transport of purified natural gas to move the gas from the production site to the consumer. Often, the compressor in this application is driven by a gas turbine which is fueled by gas bled from the pipeline. Thus, no external power source is necessary.
- in petroleum refineries, natural gas processing plants, petrochemical and chemical plants, and similar large industrial plants for compressing intermediate and end product gases.
- in refrigeration and air conditioner equipment to move heat from one place to another in refrigerant cycles.
- in gas turbine systems to compress the intake combustion air
- in storing purified or manufactured gases in a small volume, high pressure cylinders for medical, welding and other uses.
- in many various industrial, manufacturing and building processes to power all types of pneumatic tools.
- as a medium for transferring energy, such as to power pneumatic equipment.
- in pressurised aircraft to provide a breathable atmosphere of higher than ambient pressure.
- in some types of jet engines (such as turbojets and turbofans) to provide the air required for combustion of the engine fuel. The power to drive the combustion air compressor comes from the jet's own turbines.
- in SCUBA diving, hyperbaric oxygen therapy and other life support devices to store breathing gas in a small volume such as in diving cylinders.
- in submarines, to store air for later use in displacing water from buoyancy chambers, for adjustment of depth.
- in turbochargers and superchargers to increase the performance of internal combustion engines by increasing mass flow.
- in rail and heavy road transport to provide compressed air for operation of rail vehicle brakes or road vehicle brakes and various other systems (doors, windscreen wipers, engine/gearbox control, etc.).
- in miscellaneous uses such as providing compressed air for filling pneumatic tires.
- in the case of the fire piston and the heat pump, the desired outcome is the temperature rise of the gas, and compressing the gas is only a means to that end.

## Chapter 19

# Pneumatics Automation

Fluid is a substance that deforms continuously on the application of shear stress, no matter how much small is it. Fluid comprises both gases and liquid. The technique of using liquid for power transmission is called as hydraulics while which uses gases for power transmission is called Pneumatics.In most hydraulics system mineral oils will be used while in most pneumatic system atmospheric air will be used.

### Principle behind fluid power

The basic principle which governs any fluid system is the pascal law. The law applies to fluid power transmission. The other laws which will be used in the analysis, design and manufacturing of any fluid system are Boyle's law, Charles's law and Bernoulli theorem.

### Property of fluid

For reliable and proper working of hydraulic system the fluid used should have the following certain qualiteies. Some of them are

- Viscosity The fluid used should have its viscosity in the specified range. Higher viscosity will lead to higher friction and wear while lower viscosity will lead to leakage problems
- Viscosity Index This determines the change of viscosity with respect to temperature. Oil with High VI is prferrable
- Oxidation resistance The continuous use of oil will promote oxidation. So the oil should be able to resist oxidation
- Pour and Cloud point These determines the lowest range of temperature below which the fluid willnot transmit power
- Flash and fire point These determines the highest range of temperature above which fluid will catch fire and will cease to transmit power.
- Lubrication The fluid should be able to lubricate the moving parts in the system.
- Heat generation and transmission The amount of heat generated should be less. The fluid should have capacity to transmit the heat generated
- Corrosion resistance The fluid should not corrode the parts of the system.

Some of the most commonly used fluid for power transmission are water,emulsions,Water glycol, Synthetics, air and compressed gases

## *Parts of fluid system*

The most of fluid system will employ some or all of the following parts

- Pump or Compressor: This gives the motion to the fluid which is used to perform useful work
- Control Valves: These are used to regulate and control the flow of the fluid
- Tubes, pipes and Hoses: These carry the fluid from the pump/compressor to the actuator
- Actuator: The actual work is performed by the actuators.
- Discharge Tank: The liquid after performing work will be discharged into a tank in case of liquids /gases or will let into the atmosphere in case of air
- Seals: These prevent the leakage of fluid into the atmosphere or surroundings
- Filter, Lubricator and Regulator Circuit (FRL UNIT):These circuit are used to remove dirt present in the fluid. They will also lubricate and regulate the flow of fluid
- Accumulator: These are used to produce head which can be converted into useful work

### Cylinders

Cylinders are primary type of actuators used in fluid cicuit. The cylinder used in fluid circuit will consist the following parts

- Cylinder barrel
- Piston
- Ports
- Piston rod
- Cylinder Head
- Valves
- Seals

Whenever fluid is supplied to the cylinder the piston will move. This movement of piston is called as stroke. The piston can move in forward or reverse direction. The cylinders can be classified as double acting or single acting. In single acting cylinder work will be performed only in the forward stroke. The fluid will be supplied to the cylinder only during the forward stroke. The return stroke is achieved by the spring mounted in the cylinder. In double acting cylinder there will be two ports for the supply of fluid. Work can be obtained both at forward and reverse strokes. Directional control valves required for the easy operation of double acting cylinder.

## *Advantages of using Fluid Power*

The transmission of power through fluid has following advantages compared to the other modes

- Power transmission requires less mechanical parts. The problem of breakage of parts like gears, cams, belts and chains is not involved.
- Lesser noise and less vibration can be ensured from the system by proper installation of fluid system
- Forces can be conveyed up and down with less loss in efficiency
- System overloading can be prevented by use of automatic relief valves
- Economical compared to other modes

### Use of fluid power

The hydraulic press, invented by Englishman John Brahmah, was one of the first workable pieces of machinery developed that used hydraulics in its operation. Today, hydraulic power is used to operate many different tools and mechanisms. some of the devices which uses hydraulic power are

- Hydraulic jack
- Hydraulic doorstops
- Hydraulic brakes
- Power steering
- Tractors
- Various construction vehicles and equipments

Some devices which uses Pneumatics are

- Pneumatic drillers used in mining
- Air looms used in textile industries
- Air motors

### Difference between Hydraulics and Pneumatics

Precise control of velocity is achievable in hydraulics while due to compressible nature of gas Pneumatics cannot have precise control over velocity. In Hydraulics, self regulation action of oil can be used while in pneumatics oil mist has to be used for lubrication. The pressure range for hydraulics is 500-5000 psi while the pressure range for pneumatics is below 100 psi The air after performing work can be sent in to atmosphere whereas oil has to be discharged into a tank.