Vacuum tube

Modern vacuum tubes, mostly miniature style

In electronics, a **vacuum tube**, **electron tube** (in North America), **tube**, or **thermionic valve** or **valve** (in British English) is a device controlling electric current through a vacuum in a sealed container. The container is often thin transparent glass in a roughly cylindrical shape. The simplest vacuum tube, the diode, is similar to an incandescent light bulb with an added electrode inside. When the bulb's filament is heated red-hot, electrons are "boiled" off its surface and into the vacuum inside the bulb. If the electrode—called a "plate" or "anode"—is made more positive than the hot filament, a direct current flows through the vacuum to the electrode (a demonstration of the Edison effect). As the current only flows in one direction, it makes it possible to convert an alternating current applied to the filament to direct current.

The introduction of a third electrode, a grid between the filament and the plate, yields another function. A voltage applied to the grid controls the current flowing from the filament to the plate.[1] Thus, it allows the device to be used as an electronic amplifier.

Vacuum tubes are thus used for rectification, amplification, switching, or similar processing or creation of electrical signals.

The vast majority of modern day tubes consist of a sealed container with a vacuum inside, and essentially rely on thermionic emission of electrons from a hot filament or a cathode heated by the filament. Some exceptions to this are dealt with in the section about gas-filled tubes below.

Vacuum tubes were critical to the development of electronic technology, which drove the expansion and commercialization of radio broadcasting, television, radar, sound reinforcement, sound recording and reproduction, large telephone networks, analog and digital computers, and industrial process control. Although some applications had counterparts using earlier technologies such as the spark gap transmitter or mechanical computers, it was the invention of the vacuum tube with three electrodes (called a *triode*) and its capability of electronic amplification that made these technologies widespread and practical.

In most applications, solid-state devices such as transistors and other semiconductor devices have replaced tubes. Solid-state devices last longer and are smaller, more efficient, more reliable, and cheaper than tubes. Tubes can be fragile, sometimes generate significant unwanted heat, and can take many seconds—many minutes in critical applications—after powering on to warm to a temperature where they perform within operational tolerance. However, tubes still find uses where solid-state devices have not been developed, are impractical, or where a tube has superior performance, as with some devices in professional audio and high-power radio transmitters. Tubes are still produced for such applications.

Tubes are less likely than semiconductor devices to be destroyed by the electromagnetic pulse produced by nuclear explosions[2] and geomagnetic storms produced by giant solar flares.[3]

Classifications

One domain of classification of vacuum tubes uses the number of active electrodes, neglecting the filament or heater in devices with indirectly-heated cathodes (where the heater is electrically separate from the cathode). A device with two active elements is a diode, usually used for rectification. Devices with three elements are triodes used for amplification and switching. Additional electrodes create tetrodes, pentodes, and so forth, which have multiple additional functions made possible by the additional controllable electrodes.

Other classifications are:

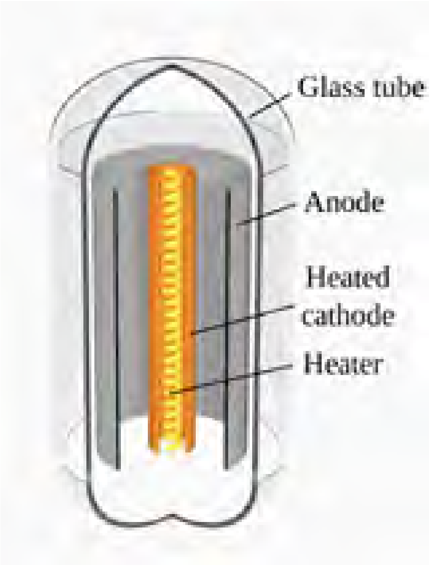
- by frequency range (audio, radio, VHF, UHF, microwave),
- by power rating (small-signal, audio power, high-power radio transmitting),
- by design (e.g., sharp- versus remote-cutoff in some pentodes)
- by application (receiving tubes, transmitting tubes, amplifying or switching, rectification, mixing),
- special qualities (long life, very low microphonic and low noise audio amplification, and so on).

Multiple classifications may apply to a device; for example similar dual triodes can be used for audio preamplification and as flip-flops in computers, although linearity is important in the former case and long life in the latter.

Tubes have different functions, such as cathode ray tubes which create a beam of electrons for display purposes (such as the television picture tube) in addition to more specialized functions such as electron microscopy and electron beam lithography. X-ray tubes are also vacuum tubes. Phototubes and photomultipliers rely on electron flow through a vacuum, though in those cases electron emission from the cathode depends on energy from photons rather than thermionic emission. Since these sorts of "vacuum tubes" have functions other than electronic amplification and rectification they are described in their own articles.

Description

A vacuum tube consists of two or more electrodes in a vacuum inside an airtight enclosure. Most tubes have glass envelopes, though ceramic and metal envelopes (atop insulating bases) have been used. The electrodes are attached to leads which pass through the envelope via an airtight seal. On most tubes, the leads, in the form of pins, plug into a tube socket for easy replacement of the tube (tubes were by far the most common cause of failure in electronic equipment, and consumers were expected to be able to replace tubes themselves). Some tubes had an electrode terminating at a top cap which reduced interelectrode capacitance to improve high-frequency performance, kept a possibly very high plate voltage away from lower voltages, and could accommodate one more electrode than allowed by the base.



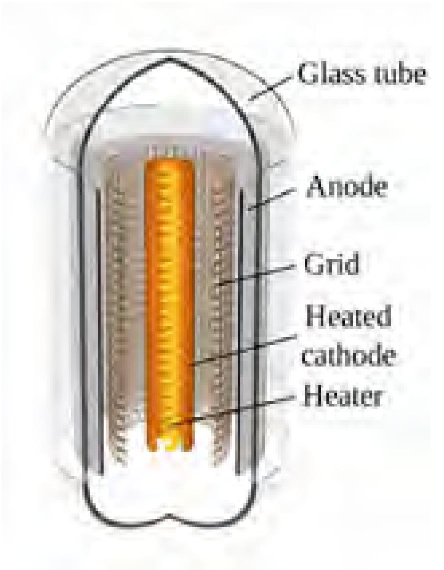
Vacuum tube diode: electrons from the hot cathode flow towards the positive anode, but not vice versa

The earliest vacuum tubes evolved from incandescent light bulbs, containing a filament sealed in an evacuated glass envelope. When hot, the filament releases electrons into the vacuum, a process called thermionic emission. A second electrode, the anode or *plate*, will attract those electrons if it is at a more positive voltage. The result is a net flow of electrons from the filament to plate. However, electrons cannot flow in the reverse direction because the plate is not heated and does not emit electrons. The filament (*cathode*) has a dual function: it emits electrons when heated; and, together with the plate, it creates an electric field due to the potential difference between them. Such a tube with only two electrodes is termed a diode, and is used for rectification. Since current can only pass in one direction, such a diode (or *rectifier*) will convert alternating current (AC) to pulsating DC. This can therefore be used in a DC power supply, and is also used as a demodulator of amplitude modulated (AM) radio signals and similar functions.

While early tubes used the directly heated filament as the cathode, most (but not all) more modern tubes employed indirect heating. A separate element was used for the cathode. Inside the cathode, and electrically insulated from it, was the filament or *heater*. Thus the heater did not function as an electrode, but simply served to heat the cathode sufficiently for it to emit electrons by thermionic emission. This allowed all the tubes to be heated through a common circuit (which can as well be AC) while allowing each cathode to arrive at a voltage independently of the others, removing an unwelcome constraint on circuit design.

The filaments require constant and often considerable power, even when amplifying signals at the microwatt level. Power is also dissipated when the electrons from the cathode slam into the anode (plate) and heat it; this can occur even in an idle amplifier due to quiescent currents necessary to ensure linearity and low distortion. In a power amplifier, this heating can be considerable and can destroy the tube if driven beyond its safe limits. Since the tube contains a vacuum, the anodes in most small and medium power tubes are cooled by radiation through the glass envelope. In some special high power applications, the anode forms part of the vacuum envelope to conduct heat to an external heat sink, usually cooled by a blower.

Klystrons and magnetrons often operate their anodes (called **collectors** in klystrons) at ground potential to facilitate cooling, particularly with water, without high voltage insulation. These tubes instead operate with high negative voltages on the filament and cathode.



Vacuum tube triode: voltage applied to the grid controls plate (anode) current.

Except for diodes, additional electrodes are positioned between the cathode and the plate (anode). These electrodes are referred to as grids as they are not solid electrodes but sparse elements through which electrons can pass on their way to the plate. The vacuum tube is then known as a triode, tetrode, pentode, etc., depending on the number of grids. A triode has three electrodes: the anode, cathode, and one grid, and so on. The first grid, known as the control grid, (and sometimes other grids) transforms the diode into a *voltage-controlled device*: the voltage applied to the control grid affects the current between the cathode and the plate. When held negative with respect to the cathode, the control grid creates an electric field which repels electrons emitted by the cathode, thus reducing or even stopping the current between cathode and anode. As long as the control grid is negative relative to the cathode, essentially no current flows into it, yet a change of several volts on the control grid is sufficient to make a large difference in the plate current, possibly changing the output by hundreds of volts (depending on the circuit). The solid-state device which operates most like the pentode tube is the junction field-effect transistor (JFET), although vacuum tubes typically operate at over a hundred volts, unlike most semiconductors in most applications.

History and development

The 19th century saw increasing research with evacuated tubes, such as the Geissler and Crookes tubes. Famous scientists who experimented with such tubes included Thomas Edison, Eugen Goldstein, Nikola Tesla, and Johann Wilhelm Hittorf among many others. With the exception of early light bulbs, such tubes were only used in scientific research or as novelties. The groundwork laid by these scientists and inventors, however, was critical to the development of subsequent vacuum tube technology.

Although thermionic emission was originally reported in 1873 by Frederick Guthrie, it was Thomas Edison's 1884 investigation that spurred future research, the phenomenon thus becoming known as the "Edison effect". Edison patented what he found,[4] but he did not understand the underlying physics, nor did he have an inkling of the potential value of the discovery. It wasn't until the early 20th century that the rectifying property of such a device was utilized, most notably by John Ambrose Fleming, who used the diode tube to detect (demodulate) radio signals. Lee De Forest's 1906 "audion" was also developed as a radio detector, and soon led to the development of the triode tube. This was essentially the first electronic amplifier, leading to great improvements in telephony (such as the first coast-to-coast telephone line in the US) and revolutionizing the technology used in radio transmitters and receivers. The electronics revolution of the 20th century arguably began with the invention of the triode vacuum tube.

Diodes

The English physicist John Ambrose Fleming worked as an engineering consultant for firms including Edison Telephone and the Marconi Company. In 1904, as a result of experiments conducted on Edison effect bulbs imported from the USA, he developed a device he called an "oscillation valve" (because it passes current in only one direction). The heated filament, or cathode, was capable of thermionic emission of electrons that would flow to the *plate* (or *anode*) when it was at a higher voltage. Electrons, however, could not pass in the reverse direction because the plate was not heated and thus not capable of thermionic emission of electrons.

Later known as the Fleming valve, it could be used as a rectifier of alternating current and as a radio wave detector. This greatly improved the crystal set which rectified the radio signal using an early solid-state diode based on a crystal and a so-called cat's whisker. Unlike modern semiconductors, such a diode required painstaking adjustment of the contact to the crystal in order for it to rectify. The tube was relatively immune to vibration, and thus vastly superior on shipboard duty, particularly for navy ships with the shock of weapon fire commonly knocking the sensitive but delicate galena off its sensitive point (the tube was in general no more sensitive a radio detector, but was adjustment free). The diode tube was a reliable alternative for detecting radio signals. Higher power diode tubes or *power rectifiers* found their way into power supply applications until they were eventually replaced by silicon rectifiers in the 1960s.

Triodes

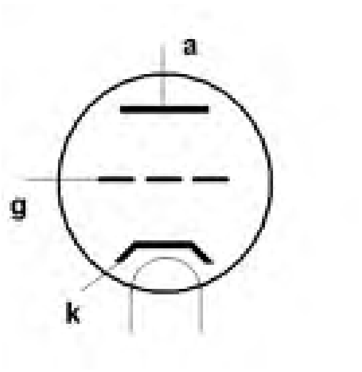
Originally, the only use for tubes in radio circuits was for rectification, not amplification. In 1906, Robert von Lieben filed for a patent[5] for a cathode ray tube which included magnetic deflection. This could be used for amplifying audio signals and was intended for use in telephony equipment. He would later go on to help refine the triode vacuum tube.


Vacuum tube with plate (anode) cut open revealing grid

However, it was Lee De Forest who is credited with inventing the triode tube in 1907 while continuing experiments to improve his original Audion tube, a crude forerunner of the triode. By placing an additional electrode between the filament (cathode) and plate (anode), he discovered the ability of the resulting device to amplify signals of all frequencies. As the voltage applied to the so-called control grid (or simply "grid") was lowered from the cathode's voltage to somewhat more negative voltages, the amount of current from the filament to the plate would be reduced. The negative electrostatic field created by the grid in the vicinity of the cathode would inhibit thermionic emission and reduce the current to the plate. Thus, a few volts' difference at the grid would make a large change in the plate current and could lead to a much larger voltage change at the plate; the result was voltage and power amplification.


Triodes as they evolved over 40 years of tube manufacture, from the RE16 in 1918 to a 1960s era miniature tube.

In 1907, De Forest filed for a patent[6] for such a three-electrode version of his original Audion tube for use as an electronic amplifier in radio communications. This eventually became known as the triode.



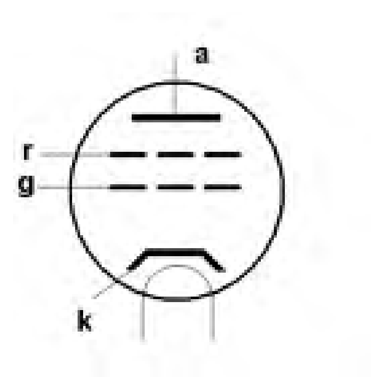
Triode symbol. From top to bottom: plate (anode), control grid, cathode, heater (filament)

De Forest's device was not a *hard vacuum* tube, as he erroneously believed that it depended on the presence of residual gas remaining after evacuation. In its Audion leaflets, the De Forest company even warned against any operation which might lead to too high a vacuum.[*citation needed*] The Finnish inventor Eric Tigerstedt significantly improved on the original triode design in 1914, while working on his sound-on-film process in Berlin, Germany. The first true vacuum triodes in production were the Pliotrons developed by Irving Langmuir at the General Electric research laboratory (Schenectady, New York) in 1915. Langmuir was one of the first scientists to realize that a harder vacuum would improve the amplifying behaviour of the triode. Pliotrons were closely followed by the French 'R' type which was in widespread use by the allied military by 1916. These two types were the first true hard vacuum tubes; early diodes and triodes performed as such despite a rather high residual gas pressure. Techniques to produce and maintain better vacua in tubes were then developed. Historically, vacuum levels in production vacuum tubes typically ranged from 10 µPa down to 10 nPa.

The non-linear operating characteristic of the triode caused early tube audio amplifiers to exhibit harmonic distortion at low volumes. This is not to be confused with the so-called overdrive distortion that tube amplifiers exhibit when driven beyond their linear region (known as tube sound). Plotting plate current as a function of applied grid voltage, it was seen that there was a range of grid voltages for which the transfer characteristics were approximately linear. To use this range, a negative bias voltage had to be applied to the grid to position the DC operating point in the linear region. This was called the idle condition, and the plate current at this point the "idle current". The controlling voltage was superimposed onto the bias voltage, resulting in a linear variation of plate current in response to both positive and negative variation of the input voltage around that point. This concept is called *grid bias*. Many early radio sets had a third battery called the "C battery" (unrelated to the present-day C cell) whose positive terminal was connected to the cathode of the tubes (or "ground" in most circuits) and whose negative terminal supplied this bias voltage to the grids of the tubes. Later circuits, after tubes were made with heaters isolated from their cathodes, used cathode biasing, avoiding the need for a separate negative power supply. However C batteries continued to be included in some equipment even when the "A" and "B" batteries had been replaced by power from the AC mains. That was possible because there was essentially no current draw on these batteries; they could thus last for many years (often longer than all the tubes) without requiring replacement.

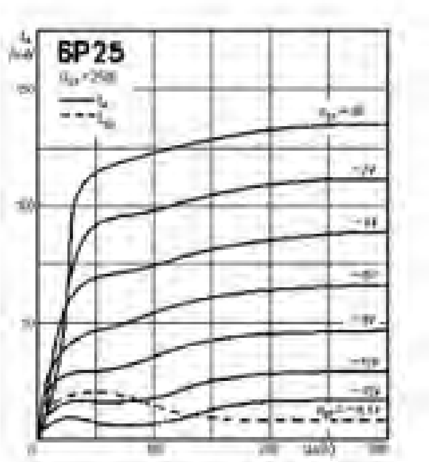
When triodes were first used in radio transmitters and receivers, it was found that tuned amplification stages had a tendency to oscillate unless their gain was very limited. This was due to the parasitic capacitance between the plate (the amplifier's output) and the control grid (the amplifier's input), known as the Miller capacitance. Eventually the technique of *neutralization* was developed whereby the RF transformer connected to the plate (anode) would include an additional winding in the opposite phase. This winding would be connected back to the grid through a small capacitor, and when properly adjusted would cancel the Miller capacitance. This technique was employed and led to the success of the Neutrodyne radio during the 1920s. However, neutralization required careful adjustment and proved unsatisfactory when used over a wide ranges of frequencies.

Tetrodes and pentodes



Tetrode symbol. From top to bottom: plate (anode), screen grid, control grid, cathode, heater (filament)

To combat the stability problems and limited voltage gain due to the Miller effect, the physicist Walter H. Schottky invented the tetrode tube in 1919. He showed that the addition of a second grid, located between the control grid and the plate (anode), known as the *screen grid*, could solve these problems. ("Screen" in this case refers to electrical "screening" or shielding, not physical construction: all "grid" electrodes in between the cathode and plate are "screens" of some sort rather than solid electrodes since they must allow for the passage of electrons directly from the cathode to the plate). A positive voltage slightly lower than the plate (anode) voltage was applied to it, and was bypassed (for high frequencies) to ground with a capacitor. This arrangement decoupled the anode and the control grid, essentially eliminating the Miller capacitance and its associated problems. Consequently, higher voltage gains from a single tube became possible, reducing the number of tubes required in many circuits. This two-grid tube is called a *tetrode*, meaning four active electrodes, and was common by 1926.

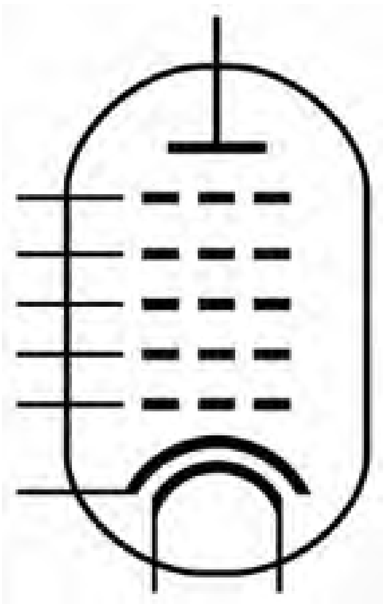


At certain values of plate voltage and current, the tetrode characteristic curves are kinked due to secondary emission.

However, the tetrode had one new problem. In any tube, electrons strike the anode with sufficient energy to cause the emission of electrons from its surface. In a triode this so-called secondary emission of electrons is not important since they are simply re-captured by the more positive anode (plate). But in a tetrode they can be captured by the screen grid (thus also acting as an anode) since it is also at a high voltage, thus robbing them from the plate current and reducing the amplification of the device. Since secondary electrons can outnumber the primary electrons, in the worst case, particularly as the plate voltage dips below the screen voltage, the plate current can decrease with increasing plate voltage. This is the so-called "tetrode kink" and is an example of negative resistance which can itself cause instability.[7] The otherwise undesirable negative resistance was exploited to produce an extremely simple oscillator circuit only requiring connection of the plate to a resonant LC circuit to oscillate; this was effective over a wide frequency range. The so-called dynatron oscillator thus operated on the same principle of negative resistance as the tunnel diode oscillator many years later. Another undesirable consequence of secondary emission is that in extreme cases enough charge can flow to the screen grid to overheat and destroy it. Later tetrodes had anodes treated to reduce secondary emission; earlier ones such as the type 77 sharp-cutoff pentode connected as a tetrode made better dynatrons.

The solution was to add another grid between the screen grid and the main anode, called the suppressor grid (since it suppressed secondary emission current toward the screen grid). This grid was held at the cathode (or "ground") voltage and its negative voltage (relative to the anode) electrostatically repelled secondary electrons so that they would be collected by the anode after all. This three-grid tube is called a pentode, meaning five electrodes. The pentode was invented in 1928 by Bernard D. H. Tellegen[*citation needed*] and became generally favored over the simple tetrode. Pentodes are made in two classes: those with the suppressor grid wired internally to the cathode (e.g. EL84/6BQ5) and those with the suppressor grid wired to a separate pin for user access (e.g. 803, 837). An alternative solution for power applications is the beam tetrode or "beam power tube", discussed below.

Multifunction and multisection tubes



The pentagrid converter contained no less than five grids between the cathode and the plate (anode).

Superheterodyne receivers require a local oscillator and mixer, which required two tubes. With the development of the pentagrid converter, these functions were combined inside a single tube which applied the RF signal to the control grid, but also implemented the local oscillator using additional grids. Various alternatives such as using a combination of a triode with a hexode and even an octode have been used for this purpose. The additional grids include both control grids (at a low potential) and screen grids (at a high voltage). Many designs used such a screen grid as an additional anode to provide feedback for the oscillator function, whose current was added to that of the incoming radio frequency signal. Due to the large oscillating signal non-linearity of the tube response caused frequency mixing, seen on the plate current (output) of such a "converter" circuit. The difference frequency between that of the incoming signal and that of the oscillator was selected by a tuned transformer, becoming the input to the receiver's intermediate frequency (IF) amplifier.

The pentagrid converter such as the 12BE6 thus became widely used in AM receivers including the miniature tube version of the "All American Five". Octodes such as the 7A8 were rarely used in the US, but much more common in Europe, particularly in battery operated radios where the lower power consumption was an advantage.

To further reduce the cost and complexity of radio equipment, two separate vacuum tubes could be combined in the bulb of a single tube, a so-called *multisection tube*. An early example was the Loewe 3NF. This 1920s device had 3 triodes in a single glass envelope together with all the fixed capacitors and resistors required to make a complete radio receiver. As the Loewe set had only one tube socket, it was able to substantially undercut the competition since, in Germany, state tax was levied by the number of sockets. However, reliability was compromised, and production costs for the tube were much greater. In a sense, these were akin to integrated circuits. In the US, Cleartron briefly produced the "Multivalve" triple triode for use in the Emerson Baby Grand receiver. This Emerson set also had a single tube socket, but because it used a four-pin base, the additional element connections were made on a "mezzanine" platform at the top of the tube base.

Popular 12AX7 dual triode

By 1940 multisection tubes had become commonplace. There were constraints, however, due to patents and other licensing considerations (see British Valve Association). Constraints due to the number of external pins (leads) often forced the functions to share some of those external connections such as their cathode connections (in addition to the heater connection). The RCA Type 55 was a double diode triode used as a detector, automatic gain control rectifier and audio preamplifier in early AC powered radios. These sets often included the 53 Dual Triode Audio Output. Another early type of multi-section tube, the 6SN7, is a "dual triode" which performs the functions of two triode tubes, while taking up half as much space and costing less. The 12AX7 is a dual "high mu" (high voltage gain[8][9][10]) triode in a miniature enclosure, and became widely used in audio signal amplifiers, instruments, and guitar amplifiers.

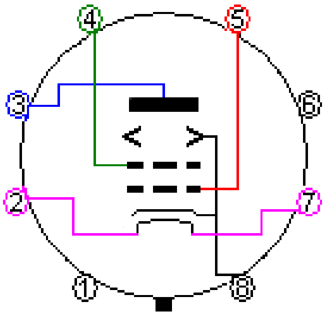
The introduction of the miniature tube base (see below) which could have 9 pins, more than previously available, allowed other multi-section tubes to be introduced, such as the 6GH8/ECF82 triode-pentode, quite popular in television receivers. The desire to include even more functions in one envelope resulted in the General Electric Compactron which had 12 pins. A typical example, the 6AG11, contained two triodes and two diodes.

Some otherwise conventional tubes do not fall into standard categories; the 6JH8 had several common grids, followed by a pair of beam deflection electrodes which deflected the current towards either of two anodes. It was sometimes known as the 'sheet beam' tube, and was used in some color TV sets for demodulation of synchronous signals, as for example for color demodulation.

Compactron tube: 12AE10, dual pentode

Beam power tubes

The beam power tube is usually a tetrode with the addition of beam-forming electrodes, which take the place of the suppressor grid. These angled plates (not to be confused with the *anode*) focus the electron stream onto certain spots on the anode which can withstand the heat generated by the impact of massive numbers of electrons, while also providing pentode behavior. The positioning of the elements in a beam power tube uses a design called "critical-distance geometry", which minimizes the "tetrode kink", plate to control grid capacitance, screen grid current, and secondary emission from the anode, thus increasing power conversion efficiency. The control grid and screen grid are also wound with the same pitch, or number of wires per inch.



Beam power tube symbol and pinout for 6L6

6L6 tubes in glass envelopes

Aligning the grid wires also helps to reduce screen current, which represents wasted energy. This design helps to overcome some of the practical barriers to designing high-power, high-efficiency power tubes. 6L6 was the first popular beam power tube, introduced by RCA in 1936. Corresponding tubes in Europe were the KT66, KT77 and KT88 made by the Marconi-Osram Valve subsidiary of GEC (the KT standing for "Kinkless Tetrode").

"Pentode operation" of beam power tubes is often described in manufacturers' handbooks and data sheets, resulting in some confusion in terminology.

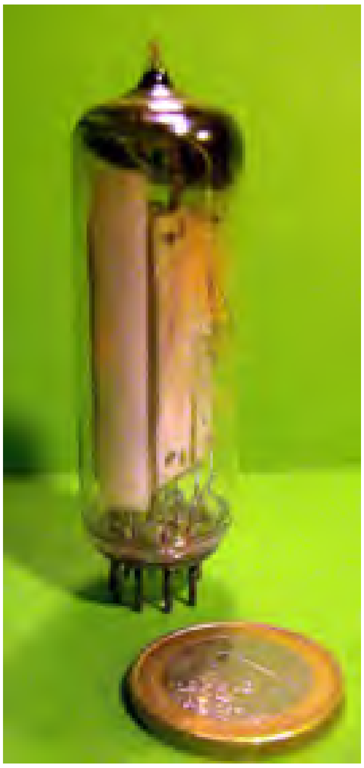
Variations of the 6L6 design are still widely used in tube guitar amplifiers, making it one of the longest-lived electronic device families in history. Similar design strategies are used in the construction of large ceramic power tetrodes used in radio transmitters.

Beam power tubes can be connected as triodes for improved audio tonal quality but in triode mode deliver significantly reduced power output.

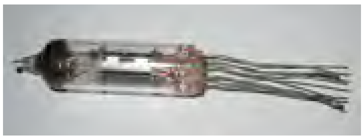
Gas-filled tubes

Gas-filled tubes such as discharge tubes and cold cathode tubes are not *hard* vacuum tubes, though are always filled with gas at less than sea-level atmospheric pressure. Types such as the voltage-regulator tube and thyratron resemble hard vacuum tubes and fit in sockets designed for vacuum tubes. Their distinctive orange, red, or purple glow during operation indicates the presence of gas; electrons flowing in a vacuum do not produce light within that region. These types may still be referred to as "electron tubes" as they do perform electronic functions. High-power rectifiers use mercury vapor to achieve a lower forward voltage drop than high-vacuum tubes.

Miniature tubes



PM84 Miniature *Magic Eye* indicator tube, alongside a euro coin



Subminiature CV4501 tube, 35 mm long x 10 mm diameter (excluding leads)

Early tubes used a metal or glass envelope atop an insulating bakelite base. In 1938 a technique was developed to instead use an all-glass construction[11] with the pins fused in the glass base of the envelope. This was used in the design of a much smaller tube outline, known as the miniature tube, having 7 or 9 pins. Making tubes smaller reduced the voltage that they could work at, and also the power of the filament. Miniature tubes became predominant in consumer applications such as radio receivers and hi-fi amplifiers. However the larger older styles continued to be used especially as higher power rectifiers, in higher power audio output stages and as transmitting tubes.

Subminiature tubes with a size roughly that of half a cigarette were used in hearing-aid amplifiers. These tubes did not have pins plugging into a socket but were soldered in place. The "acorn" valve (named due to its shape) was also very small, as was the metal-cased nuvistor, about the size of a thimble. The small size supported especially high-frequency operation; nuvistors were used in UHF television tuners until replaced by high-frequency transistors.

Improvements in construction and performance

The earliest vacuum tubes strongly resembled incandescent light bulbs and were made by lamp manufacturers, who had the equipment needed to manufacture glass envelopes and the vacuum pumps required to evacuate the enclosures. De Forest used Heinrich Geissler's mercury displacement pump, which left behind a partial vacuum. The development of the diffusion pump in 1915 and improvement by Irving Langmuir led to the development of high-vacuum tubes. After World War I, specialized manufacturers using more economical construction methods were set up to fill the growing demand for broadcast receivers. Bare tungsten filaments operated at a temperature of around 2200 °C. The development of oxide-coated filaments in the mid-1920s reduced filament operating temperature to a dull red heat (around 700 °C), which in turn reduced thermal distortion of the tube structure and allowed closer spacing of tube elements. This in turn improved tube gain, since the gain of a triode is inversely proportional to the spacing between grid and cathode. Bare tungsten filaments remain in use in small transmitting tubes but are brittle and tend to fracture if handled roughly – e.g. in the postal services. These tubes are best suited to stationary equipment where impact and vibration is not present.

Indirectly heated cathodes

The desire to power electronic equipment using AC mains power faced a difficulty with respect to the powering of the tubes' filaments, as these were also the cathode of each tube. Powering the filaments directly from a power transformer introduced mains-frequency (50 or 60 Hz) hum into audio stages. The invention of the "equipotential cathode" reduced this problem, with the filaments being powered by a balanced AC power transformer winding having a grounded center tap.

A superior solution, and one which allowed each cathode to "float" at a different voltage, was that of the indirectly-heated cathode: a cylinder of oxide-coated nickel acted as electron-emitting cathode, and was electrically isolated from the filament inside it. The filament, no longer electrically connected to the tube's electrodes, became simply known as a "heater", and could as well be powered by AC without any introduction of hum.[12] In the 1930s indirectly heated cathode tubes became widespread in equipment using AC power. Directly heated cathode tubes continued to be widely used in battery-powered equipment as their filaments required considerably less power than the heaters required with indirectly-heated cathodes.

RCA 6DS4 "Nuvistor" triode, circa 20 mm high by 11 mm diameter

Indirectly heated cathodes enable the cathode circuit to be separated from the heater circuit, thereby eliminating hum and mains noise from the signal circuit.

Tubes designed for high gain audio applications may have twisted heater wires to cancel out stray hum fields from being induced into the cathode.

Heaters may be energised with either alternating current (AC) or direct current (DC). DC is often used where low hum is required but because of the high current at low voltage in the heater circuit, DC power was not viable until the advent of low cost solid state rectifiers and appropriate large capacitance filter capacitors.

Use in electronic computers

The 1946 ENIAC computer used 17,468 vacuum tubes and consumed 150 kW of power

Vacuum tubes, which could be used for switching, made electronic computing possible for the first time, but the cost and relatively short mean time to failure of tubes were limiting factors. "The common wisdom was that valves—which, like light bulbs, contained a hot glowing filament—could never be used satisfactorily in large numbers, for they were unreliable, and in a large installation too many would fail in too short a time".[13] Tommy Flowers, who later designed *Colossus*, "discovered that, so long as valves were switched on and left on, they could operate reliably for very long periods, especially if their 'heaters' were run on a reduced current".[13] In 1934 Flowers built a successful experimental installation using over 3,000 tubes in small independent modules; when a tube failed, it was possible to switch off one module and keep the others going, thereby reducing the risk of another tube failure being caused; this installation was accepted by the Post Office (who operated telephone exchanges). Flowers was also a pioneer of using tubes as very fast (compared to electromechanical devices) electronic switches. Later work confirmed that tube unreliability was not as serious an issue as generally believed; the 1946 ENIAC, with over 17,000 tubes, had a tube failure (which took 15 minutes to locate) on average every two days. The quality of the tubes was a factor, and unfortunately the diversion of skilled people during the second world war lowered the general quality of tubes.[14] During the war Colossus was instrumental in breaking German codes. After the war, development continued with tube-based computers including, military computers ENIAC and Whirlwind, the Ferranti Mark 1 (the first commercially available electronic computer), and UNIVAC I, also available commercially.

There is a group of people rebuilding old computers, many solid-state, but some with tubes. Their website includes discussion of circuits, various tubes built specifically for computer use (ECC91 for general logic use, E90CC and E92CC for computer use), and other information.[15] A Colossus has been rebuilt; the only other tube computer being restored as of 2011[16] was the very reliable but very slow Harwell WITCH.

Colossus

Flowers's Colossus and its successor Colossus Mk2 were built by the British during World War II to substantially speed up the task of breaking the German high level Lorenz encryption. Using about 1,500 vacuum tubes (2,400 for Mk2), Colossus replaced an earlier machine based on relay and switch logic (the Heath Robinson). Colossus was able to break in a matter of hours messages that had previously taken several weeks; it was also much more reliable.[13] Colossus was the first use of vacuum tubes *working in concert* on such a large scale for a single machine.[13]

Once Colossus was built and installed, it ran continuously, powered by dual redundant diesel generators, the wartime mains supply being considered too unreliable. The only time it was switched off was for conversion to Mk2, with the addition of more tubes. Another nine Colossus Mk2s were built, and all ten machines were surprisingly reliable. The ten machines drew 15 kilowatts of power each continuously, largely for the tube heaters.

A working Colossus has been rebuilt, and was switched on in 1996, followed by a Mk2 in 2004; a wartime German ciphertext was (belatedly) deciphered in 2007.[17]

Whirlwind and "special-quality" tubes

To meet the reliability requirements of the 1951 US digital computer Whirlwind, "special-quality" tubes with extended life, and a long-lasting cathode in particular, were produced. The problem of short lifetime was traced to evaporation of silicon, used in the tungsten alloy to make the heater wire easier to draw. Elimination of silicon from the heater wire alloy (and more frequent replacement of the wire drawing dies) allowed production of tubes that were reliable enough for the Whirlwind project. The tubes developed for Whirlwind were later used in the giant SAGE air-defense computer system. High-purity nickel tubing and cathode coatings free of materials that can poison emission (such as silicates and aluminium) also contribute to long cathode life. The first such "computer tube" was Sylvania's 7AK7 of 1948. By the late 1950s it was routine for special-quality small-signal tubes to last for hundreds of thousands of hours, if operated conservatively. This increased reliability also made mid-cable amplifiers in submarine cables possible.

Heat generation and transfer

A considerable amount of heat is produced when tubes operate, both from the filament (heater) but also from the stream of electrons bombarding the plate. The requirements for heat removal can significantly change the appearance of high-power vacuum tubes. Although the miniature tube style became predominant in consumer equipment, high power audio amplifiers and rectifiers would still require the larger "octal" style of enclosure. Transmitting tubes could be much larger still.

The anode (plate) of this transmitting triode has been designed to dissipate up to 500 W of heat

Most tubes produce heat from two sources during operation. The first source is the filament or heater. Some tubes contain a *directly-heated cathode*. This is a filament similar to an incandescent electric lamp; some types glow brightly like a lamp, but most glow a dim orange-red. The "bright emitter" types possess a tungsten filament alloyed with 1–3% thorium which reduces the work function of the metal, giving it the ability to emit sufficient electrons at about 2000 degrees Celsius. The "dull emitter" types also possess a tungsten filament, but it is coated in a mixture of calcium, strontium and barium oxides, which emits electrons easily at much lower temperatures due to a monolayer of mixed alkali earth metals coating the tungsten; these only reach 800–1000 degrees Celsius.

The second form of cathode is the *indirectly-heated* form which usually consists of a nickel cylinder, coated on the outside with the same strontium, calcium, barium oxide mix used in the "dull emitter" directly heated types; inside the cylinder is a tungsten filament to heat it. This filament is usually uncoiled and coated in a layer of alumina (aluminium oxide) that insulates it from the actual cathode. This form of construction allows for a much greater electron-emitting area and allows the cathode to be held at a potential difference, typically 150 volts more positive than the heater or 50 volts more negative than the heater. For small-signal tubes such as those used in radio receivers, heaters consume between 50 mW and 5 watts, (directly heated), or between 500 mW and 8 watts for indirectly-heated types. Thus, even a small signal amplifier might consume a watt of power just to warm its heater, compared to the milliwatts (or less) that a modern semiconductor amplifier would require for the same function. Even in power amplifiers the filament power may be responsible for an appreciable reduction in efficiency.

The second source of heat generated is at the plate (anode), as electrons accelerated by its high voltage strike it, depositing their kinetic energy there and raising its temperature. In tubes used in power amplifiers or transmitter output stages, this source of heat will far exceed the power due to the cathode heater. The plates of improperly operated or overloaded beam power tubes can sometimes become visibly red hot; this should never occur under normal operation of consumer electronics and is a precursor to tube failure.

Heat escapes the device by black body radiation from the anode (plate) as infrared radiation. Convection is not possible in most tubes since the anode is surrounded by vacuum. Considerations of heat removal can affect the overall appearance of some tubes. The anode is often treated to make its surface less shiny and darker in the infrared (see black body radiator). The screen grid may also generate considerable heat, which is radiated toward the plate which must reradiate that additional heat along with the heat it generates itself. Limits to screen grid dissipation, in addition to plate dissipation, are listed for power devices. If these are exceeded then tube failure is likely.

Tubes used as power amplifier stages for radio transmitters may have additional heat exchangers, cooling fans, radiator fins, or other measures to improve heat transfer at the anode (plate). High power transmitting tubes may have the surface of their anodes external to the tube, allowing for water cooling or evaporative cooling. Such a water cooling system must be electrically isolated to withstand the high voltage present on the anode.

Tubes which generate relatively little heat, such as the 1.4 volt filament directly-heated tubes designed for use in battery-powered equipment, often have shiny metal anodes. 1T4, 1R5 and 1A7 are examples. Gas-filled tubes such as thyratrons may also use a shiny metal anode, since the gas present inside the tube allows for heat convection from the anode to the glass enclosure.

The outer electrode in most tubes is the anode (plate). Some small-signal types, such as sharp and remote cut-off R.F. and A.F. pentodes and some pentagrid converters have a shield fitted around all the electrodes enclosing the anode. This shield is sometimes a solid metal sheet, treated to make it dull and gray so that it can itself reradiate heat generated from within. Sometimes it is fabricated from expanded metal mesh, acting as a Faraday cage but allowing sufficient infrared radiation from the anode to escape. Types 6BX6/EF80 and 6BK8/EF86 are typical examples of this shielded type using expanded mesh. Types 6AU6/EF94 and 6BE6/EK90 are examples which use a gray sheet metal cylindrical shield.

Tube packages

Metal cased tubes with "octal" bases

Most modern tubes have glass envelopes, but metal, fused quartz (silica) and ceramic have also been used. A first version of the 6L6 used a metal envelope sealed with glass beads, while a glass disk fused to the metal was used in later versions. Metal and ceramic are used almost exclusively for power tubes above 2 kW dissipation. The nuvistor was a modern receiving tube using a very small metal and ceramic package.

The internal elements of tubes have always been connected to external circuitry via pins at their base which plug into a socket. After all, unlike modern semiconductor devices which are mostly soldered in place, tubes needed to be replaced rather frequently . Subminiature tubes were produced using wire leads rather than sockets, however these were restricted to rather specialized applications. In addition to the connections at the base of the tube, many early triodes connected the grid using a metal cap at the top of the tube; this reduces stray capacitance between the grid and the plate leads. Tube caps were also used for the plate (anode) connection, particularly in transmitting tubes and tubes using a very high plate voltage.

High power GS-9B triode transmitting tube with heat sink at bottom.

High-power tubes such as transmitting tubes have packages designed more to enhance heat transfer. In some tubes, the metal envelope is also the anode. The 4CX1000A is an external anode tube of this sort. Air is blown through an array of fins attached to the anode, thus cooling it. Power tubes using this cooling scheme are available up to 150 kW dissipation. Above that level, water or water-vapor cooling are used. The highest-power tube currently available is the Eimac 4CM2500KG, a forced water-cooled power tetrode capable of dissipating 2.5 megawatts. (By comparison, the largest power transistor can only dissipate about 1 kilowatt.)

Names

In many cases manufacturers and the military gave tubes designations which said nothing about their purpose (e.g., 1614). In the early days some manufacturers used proprietary names which might convey some information, but only about their products; the KT66 and KT88 were "**K**inkless **T**etrodes". Later, consumer tubes were given names which conveyed some information. In the US, names comprise a number, followed by one or two letters, and a number. The first number is the (rounded) heater voltage; the letters designate a particular tube but say nothing about its structure; and the final number is the total number of electrodes (without distinguishing between, say, a tube with many electrodes, or two sets of electrodes in a single envelope—a double triode, for example). For example the 12AX7 is a double triode (two sets of three electrodes plus heater) with a 12.6V heater (which, as it happens, can also be connected to run from 6.3V). The "AX" has no meaning.

A system widely used in Europe known as the Mullard-Philips tube designation, also extended to transistors, uses a letter, followed by one or more further letters, and a number. The type designator specifies the heater voltage or current, the functions of all sections of the tube, the socket type, and the particular tube. In this system special-quality tubes (e.g., for long-life computer use) are indicated by moving the number immediately after the first letter: the E83CC is a special-quality equivalent of the ECC83 (the European equivalent of the 12AX7), the E55L a power pentode with no consumer equivalent.

Special-purpose tubes

Some special-purpose tubes are constructed with particular gases in the envelope. For instance, voltage-regulator tubes contain various inert gases such as argon, helium or neon, which will ionize at predictable voltages. The thyratron is a special-purpose tube filled with low-pressure gas or mercury vapor. Like vacuum tubes, it contains a hot cathode and an anode, but also a control electrode which behaves somewhat like the grid of a triode. When the control electrode starts conduction, the gas ionizes, after which the control electrode can no longer stop the current; the tube "latches" into conduction. Removing anode (plate) voltage lets the gas de-ionize, restoring its non-conductive state. Some thyratrons can carry large currents for their physical size. One example is the miniature type 2D21, often seen in 1950s jukeboxes as control switches for relays. A cold-cathode version of the thyratron, which uses a pool of mercury for its cathode, is called an ignitron; some can switch thousands of amperes. Thyratrons containing hydrogen have a very consistent time delay between their turn-on pulse and full conduction; they behave much like modern silicon-controlled rectifiers, also called thyristors due to their functional similarity to thyratrons. Thyratrons have long been used in radar transmitters.

Voltage-regulator tube in operation. Low pressure gas within tube glows due to current flow.

An extremely specialized tube is the krytron, which is used for extremely precise and rapid high-voltage switching. Krytrons with certain specifications are suitable to initiate the precise sequence of detonations used to set off a nuclear weapon, and are heavily controlled at an international level.

X-ray tubes are used in medical imaging among other uses. X-ray tubes used for continuous-duty operation in fluoroscopy and CT imaging equipment may use a focused cathode and a rotating anode to dissipate the large amounts of heat thereby generated. These are housed in an oil-filled aluminium housing to provide cooling.

The photomultiplier tube is an extremely sensitive detector of light, which uses the photoelectric effect and secondary emission, rather than thermionic emission, to generate and amplify electrical signals. Nuclear medicine imaging equipment and liquid scintillation counters use photomultiplier tube arrays to detect low-intensity scintillation due to ionizing radiation.

Powering the tube

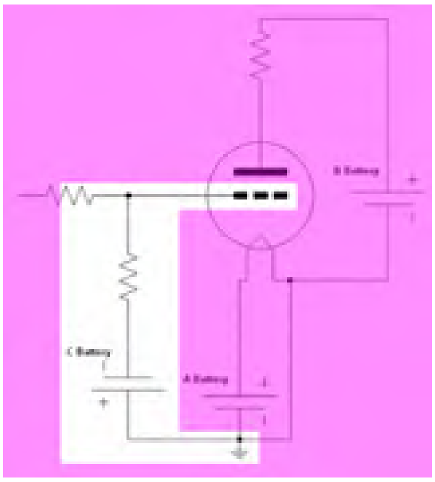
Batteries

Batteries provided the voltages required by tubes in early radio sets. Three different voltages were generally required, using three different batteries designated as the **A**, **B**, and **C** battery. The "A" battery or LT (low-tension) battery provided the filament voltage. Tube heaters were designed for single, double or triple-cell lead-acid batteries, giving nominal heater voltages of 2 V, 4 V or 6 V. In portable radios, dry batteries were sometimes used with 1.5 or 1 V heaters. Reducing filament consumption improved the life span of batteries. By 1955 towards the end of the tube era, tubes using only 50 mA down to as little as 10 mA for the heaters had been developed.[]

The high voltage applied to the anode (plate) was provided by the "B" battery or the HT (high-tension) supply or battery. These were generally of dry cell construction and typically came in 22.5, 45, 67.5, 90 or 135 volt versions.

Early sets used a grid bias battery or "C" battery which was connected to provide a *negative* voltage. Since virtually no current flows through a tube's grid connection, these batteries had very low drain and lasted the longest. Even after AC power supplies became commonplace, some radio sets continued to be built with C batteries, as they would almost never need replacing. However more modern circuits were designed using cathode biasing, eliminating the need for a third power supply voltage; this became practical with tubes using indirect heating of the cathode.

Note that the "C battery" is a designation having no relation to the 1.5 volt "C cell".



Batteries for a vacuum tube circuit. The C battery is highlighted.

AC power

Battery replacement was a major operating cost for early radio receiver users. The development of the battery eliminator, and, in 1925, batteryless receivers operated by household power, reduced operating costs and contributed to the growing popularity of radio. A power supply using a transformer with several windings, one or more rectifiers (which may themselves be vacuum tubes), and large filter capacitors provided the required direct current voltages from the alternating current source.

As a cost reduction measure, especially in high-volume consumer receivers, all the tube heaters could be connected in series across the AC supply using heaters requiring the same current and with a similar warm-up time. In one such design, a tap on the rectifier tube's heater supplied the 6 volts needed for the dial light. By deriving the high voltage from a half-wave rectifier directly connected to the AC mains, the heavy and costly power transformer was eliminated. This also allowed such receivers to operate on DC as well as standard AC mains. Many US consumer AM radio manufacturers of the era used a virtually identical circuit with the tube complement of 12BA6, 12BE6, 12AV6, 35W4 and 50C5, giving these radios the nickname All American Five or simply "Five Tube Radio." Although millions of such receivers were produced, they have now become collector's items.

Where the mains voltage was in the 100-120V range, this limited voltage proved suitable only for low-power receivers. Television receivers either required a transformer or could use a voltage doubling circuit. Where 230 V nominal mains voltage was used, television receivers as well could dispense with a power transformer.

This circuitry also allowed for "instant on" television (and radio) receivers in the later years of tube dominance. This depended on the new availability of silicon rectifiers. Rather than completely shutting off AC power to the circuitry, the set's power switch would be shunted with a silicon rectifier. When turned to the "off" position, the silicon rectifier would allow current to pass during one half of each AC cycle, keeping the tube heaters fairly warm, though not at normal operating temperature. The silicon rectifier was oriented *opposite* that of the main (tube) rectifier supplying DC power. Therefore, no power was supplied to the circuitry while the tubes stayed somewhat warm 24 hours a day. Turning the power switch on allowed current to flow in the direction required by the power supply as well as providing full power to the tubes' heaters. Since the heaters had already been running at partial power, turning the power switch on caused the set to operate within a few seconds, ending the frustrating delay for the set to "warm up."

The transformer-less power supply did present a safety issue, because the chassis of the receiver was connected to one side of the mains, presenting a shock hazard. This hazard was reduced by enclosing the chassis in an insulated case and running the AC power through a so-called interlock connection at the removable back side of the receiver. This would disconnect when the radio was opened, and so prevent a shock hazard. Technicians and tinkerers routinely bypassed this by using a separate cord, known colloquially as a "cheater cord" or "widowmaker."

Reliability

One reliability problem of tubes with oxide cathodes is the possibility that the cathode may slowly become "poisoned" by gas molecules from other elements in the tube, which reduce its ability to emit electrons. Trapped gases or slow gas leaks can also damage the cathode or cause plate (anode) current runaway due to ionization of free gas molecules. Vacuum hardness and proper selection of construction materials are the major influences on tube lifetime. Depending on the material, temperature and construction, the surface material of the cathode may also diffuse onto other elements. The resistive heaters that heat the cathodes may break in a manner similar to incandescent lamp filaments, but rarely do, since they operate at much lower temperatures than lamps.

Tube tester manufactured in 1930

The heater's failure mode is typically a stress-related fracture of the tungsten wire or at a weld point and generally occurs after accruing many thermal (power on-off) cycles. Tungsten wire has a very low resistance when at room temperature. A negative temperature coefficient device, such as a thermistor, may be incorporated in the equipment's heater supply or a ramp-up circuit may be employed to allow the heater or filaments to reach operating temperature more gradually than if powered-up in a step-function. Low-cost radios had tubes with heaters connected in series, with a total voltage equal to that of the line (mains). Following World War II, tubes intended to be used in series heater strings were redesigned to all have the same ("controlled") warm-up time. Earlier designs had quite-different thermal time constants. The audio output stage, for instance, had a larger cathode, and warmed up more slowly than lower-powered tubes. The result was that heaters that warmed up faster also temporarily had higher resistance, because of their positive temperature coefficient. This disproportionate resistance caused them to temporarily operate with heater voltages well above their ratings, and shortened their life.

Another important reliability problem is caused by air leakage into the tube. Usually oxygen in the air reacts chemically with the hot filament or cathode, quickly ruining it. Designers developed tube designs that sealed reliably. This was why most tubes were constructed of glass. Metal alloys (such as Cunife and Fernico) and glasses had been developed for light bulbs that expanded and contracted in similar amounts, as temperature changed. These made it easy to construct an insulating envelope of glass, while passing connection wires through the glass to the electrodes.

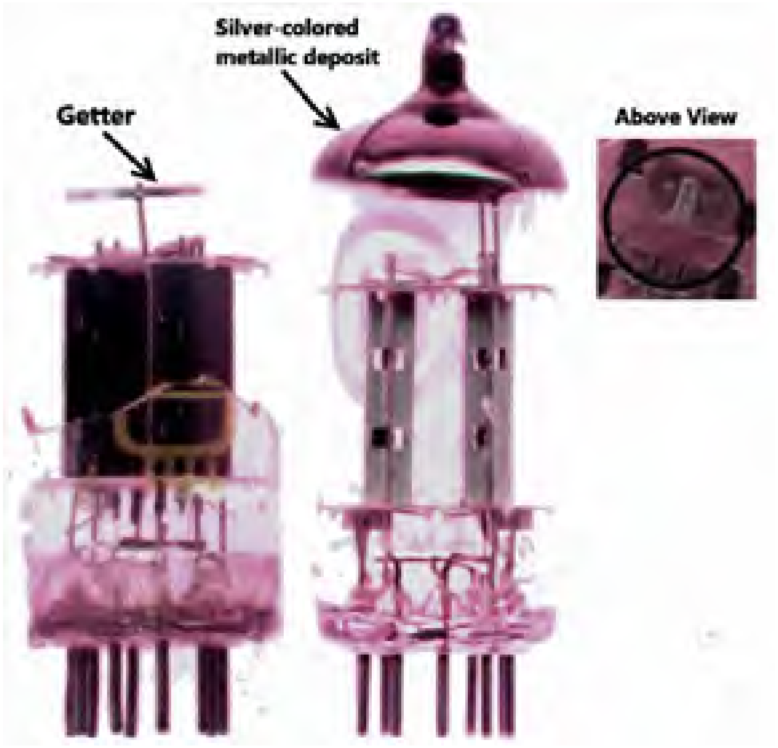
When a vacuum tube is overloaded or operated past its design dissipation, its anode (plate) may glow red. In consumer equipment, a glowing plate is universally a sign of an overloaded tube. However, some large transmitting tubes are designed to operate with their anodes at red, orange, or in rare cases, white heat.

"Special quality" versions of standard tubes were often made, designed for improved performance in some respect, such as long life, low noise, mechanical ruggedness, low microphony, for applications where the tube will spend much of its time cut off, etc. The only way to know the particular features of a special quality part is by reading the data sheet. Names may reflect the standard name (12AU7==>12AU7A, its equivalent ECC82==>E82CC, etc.), or be absolutely anything (standard and special-quality equivalents of the same tube include 12AU7, ECC82, B329, CV491, E2163, E812CC, M8136, CV4003, 6067, VX7058, 5814A and 12AU7A).[18]

The longest recorded valve life was earned by a Mazda AC/P pentode valve (serial No. 4418) in operation at the BBC's main Northern Ireland transmitter at Lisnagarvey. The valve was in service from 1935 until 1961 and had a recorded life of 232,592 hours. The BBC maintained meticulous records of their valves' lives with periodic returns to their central valve stores.[19]

Vacuum

The highest possible vacuum is desired in a tube. Remaining gas atoms will ionize and conduct electricity between the elements in an undesired manner. In a defective tube residual air pressure will lead to ionization, becoming visible as a pink-purple glow discharge between the tube elements.



Getter in opened tube; silvery deposit from getter

To prevent gases from compromising the tube's vacuum, modern tubes are constructed with "getters", which are usually small, circular troughs filled with metals that oxidize quickly, barium being the most common. While the tube envelope is being evacuated, the internal parts except the getter are heated by RF induction heating to evolve any remaining gas from the metal parts. The tube is then sealed and the getter is heated to a high temperature, again by radio frequency induction heating, which causes the getter material to vaporize and react with any residual gas. The vapor is deposited on the inside of the glass envelope, leaving a silver-colored metallic patch which continues to absorb small amounts of gas that may leak into the tube during its working life. Great care is taken with the valve design to ensure this material is not deposited on any of the working electrodes. If a tube develops a serious leak in the envelope, this deposit turns a white color as it reacts with atmospheric oxygen. Large transmitting and specialized tubes often use more exotic getter materials, such as zirconium. Early gettered tubes used phosphorus based getters and these tubes are easily identifiable, as the phosphorus leaves a characteristic orange or rainbow deposit on the glass. The use of phosphorus was short-lived and was quickly replaced by the superior barium getters. Unlike the barium getters, the phosphorus did not absorb any further gases once it had fired.

Getters act by chemically combining with residual or infiltrating gases, but are unable to counteract (non-reactive) inert gases. A known problem, mostly affecting valves with large envelopes such as Cathode Ray Tubes and camera tubes such as Iconoscopes and Orthicons/Image Orthicons, comes from **helium** infiltration. The effect appears as impaired or absent functioning, and as a diffuse glow along the electron stream inside the tube. This effect cannot be rectified (short of re-evacuation and resealing), and is responsible for working examples of such tubes becoming rarer and rarer. Unused ("New Old Stock") tubes can also exhibit inert gas infiltration, so there is no long-term guarantee of these tube types surviving into the future.

Transmitting tubes

Large transmitting tubes have carbonized tungsten filaments containing a small trace (1% to 2%) of thorium. An extremely thin (molecular) layer of thorium atoms forms on the outside of the wire's carbonized layer and, when heated, serve as an efficient source of electrons. The thorium slowly evaporates from the wire surface, while new thorium atoms diffuse to the surface to replace them. Such thoriated tungsten cathodes usually deliver lifetimes in the tens of thousands of hours. The end-of-life scenario for a thoriated-tungsten filament is when the carbonized layer has mostly been converted back into another form of tungsten carbide and emission begins to drop off rapidly; a complete loss of thorium has never been found to be a factor in the end-of-life in a tube with this type of emitter. The highest reported tube life is held by an Eimac power tetrode used in a Los Angeles radio station's transmitter, which was removed from service after 80,000 hours (~9 years) of operation[*citation needed*]. It has been saidWikipedia:Avoid weasel words that transmitters with vacuum tubes are better able to survive lightning strikes than transistor transmitters do. While it was commonly believed that at RF power levels above approx. 20 kilowatts, vacuum tubes were more efficient than solid state circuits, this is no longer the case especially in medium wave (AM broadcast) service where solid state transmitters at nearly all power levels have measurably higher efficiency. FM broadcast transmitters with solid state power amplifiers up to approx. 15 kW also show better overall mains-power efficiency than tube-based power amplifiers.

Receiving tubes

Cathodes in small "receiving" tubes are coated with a mixture of barium oxide and strontium oxide, sometimes with addition of calcium oxide or aluminium oxide. An electric heater is inserted into the cathode sleeve, and insulated from it electrically by a coating of aluminium oxide. This complex construction causes barium and strontium atoms to diffuse to the surface of the cathode and emit electrons when heated to about 780 degrees Celsius.

Failure modes

Catastrophic failures

A catastrophic failure is one which suddenly makes the vacuum tube unusable. A crack in the glass envelope will allow air into the tube and destroy it. Cracks may result from stress in the glass, bent pins or impacts; tube sockets must allow for thermal expansion, to prevent stress in the glass at the pins. Stress may accumulate if a metal shield or other object presses on the tube envelope and causes differential heating of the glass. Glass may also be damaged by high-voltage arcing.

Tube heaters may also fail without warning, especially if exposed to over voltage or as a result of manufacturing defects. Tube heaters do not normally fail by evaporation like lamp filaments, since they operate at much lower temperature. The surge of inrush current when the heater is first energized causes stress in the heater, and can be avoided by slowly warming the heaters, gradually increasing current with a NTC thermistor included in the circuit. Tubes intended for series-string operation of the heaters across the supply have a specified controlled warm-up time to avoid excess voltage on some heaters as others warm up. Directly heated filament-type cathodes as used in battery-operated tubes or some rectifiers may fail if the filament sags, causing internal arcing. Excess heater-to-cathode voltage in indirectly heated cathodes can break down the insulation between elements and destroy the heater.

Arcing between tube elements can destroy the tube. An arc can be caused by applying voltage to the anode (plate) before the cathode has come up to operating temperature, or by drawing excess current through a rectifier, which damages the emission coating. Arcs can also be initiated by any loose material inside the tube, or by excess screen voltage. An arc inside the tube allows gas to evolve from the tube materials, and may deposit conductive material on internal insulating spacers.[20]

Tube rectifiers have limited current capability and exceeding ratings – even briefly – can quickly destroy a tube.

Degenerative failures

Degenerative failures are those caused by the slow deterioration of performance over time.

Overheating of internal parts, such as control grids or mica spacer insulators, can result in trapped gas escaping into the tube; this can reduce performance. A getter is used to absorb gases evolved during tube operation, but has only a limited ability to combine with gas. Control of the envelope temperature prevents some types of gassing. A tube with an unusually high level of internal gas may exhibit a visible blue glow when plate voltage is applied. The getter (being a highly reactive metal) is effective against many atmospheric gases, but has no (or very limited) chemical reactivity to inert gases such as helium. One progressive type of failure, especially with physically large envelopes such as those used by camera tubes and cathode-ray tubes, comes from helium infiltration. The exact mechanism not clear: the metal-to-glass lead-in seals are one possible infiltration site.

Gas and ions within the tube contribute to grid current which can disturb operation of a vacuum tube circuit. Another effect of overheating is the slow deposit of metallic vapors on internal spacers, resulting in inter-element leakage.

Tubes on standby for long periods, with heater voltage applied, may develop high cathode interface resistance and display poor emission characteristics. This effect occurred especially in pulse and digital circuits, where tubes had no plate current flowing for extended times. Tubes designed specifically for this mode of operation were made.

Cathode depletion is the loss of emission after thousands of hours of normal use. Sometimes emission can be restored for a time by raising heater voltage, either for a short time or a permanent increase of a few percent. Cathode depletion was uncommon in signal tubes but was a frequent cause of failure of monochrome television cathode-ray tubes.[21] Usable life of this expensive component was sometimes extended by fitting a boost transformer to increase heater voltage.

Other failures

Vacuum tubes may have or develop defects in operation that make an individual tube unsuitable in a given device, although it may perform satisfactorily in another application. *Microphonics* refers to internal vibrations of tube elements which modulate the tube's signal in an undesirable way; sound or vibration pick-up may affect the signals, or even cause uncontrolled howling if a feedback path develops between a microphonic tube and, for example, a loudspeaker. Leakage current between AC heaters and the cathode may couple into the circuit, or electrons emitted directly from the ends of the heater may also inject hum into the signal. Leakage current due to internal contamination may also inject noise.[22] Some of these effects make tubes unsuitable for small-signal audio use, although unobjectionable for many purposes. Selecting the best of a batch of nominally identical tubes for critical applications can produce better results.

Tube pins are designed to facilitate installation and removal from its socket but, due to the high operating temperatures of these devices and/or ingress of dirt and dust over time, pins can develop non-conducting or high resistance surface films. Pins can be easily cleaned to restore conductance to normal standards.

Cooling

Like any electronic device, vacuum tubes produce heat while operating. This waste heat is one of the principal factors that affect tube life.[23] In power amplifiers, the majority of this waste heat originates in the anode though screen grids may also require cooling. For example, the screen grid in an EL34 is cooled by two small radiators or "wings" near the top of the tube. A tube's heater (filament) also contributes to the total waste heat. A tube's data sheet will normally identify the maximum power that each element may safely dissipate.

The method of anode cooling is dependent on the construction of the tube itself. Tubes used in consumer equipment have internal anodes, so cooling occurs through black body radiation from the anode (plate) to the glass envelope;[24] natural convection (air circulation) then removes the heat from the envelope. Tube shields that aided heat dispersal can be retrofitted on certain types of tube; they improve heat conduction from the surface of the tube to the shield itself by means of tens of copper tongues in contact with the glass tube, and have an opaque, black outside finish for improved heat radiation. The ability to remove heat may be further increased by forced-air cooling, and adding an external heat sink attached to the anode through the tube's enclosure. These measures are both implemented in the 4-1000A transmitting tube, whose anode was designed to operate while red hot, dissipating up to one kilowatt.[25]

The amount of heat that may be removed from a tube with an internal anode is limited.[24] Tubes with external anodes may be cooled using forced air, water, vapor, and multiphase. The 3CX10,000A7 is an example of a tube with an external anode cooled by forced air. Water, vapor, and multiphase cooling techniques all depend on the high specific heat and latent heat of water. The water-cooled 80 kg, 1.25 MW 8974 is among the largest commercial tubes available today.

In a water-cooled tube, the anode voltage appears directly on the cooling water surface, thus requiring the water to be an electrical insulator to prevent high voltage leakage through the cooling water to the radiator system. Water as usually supplied has ions which conduct electricity; deionized water, a good insulator, is required. Such systems usually have a built-in water-conductance monitor which will shut down the high-tension supply (often tens of kilovolts) if the conductance {measured in Mhos} becomes too high.

Other vacuum tube devices

Most small signal vacuum tube devices have been superseded by semiconductors, but some vacuum tube electronic devices are still in common use including the magnetron, klystron, photomultiplier, x-ray tube, traveling-wave tube and cathode ray tube. The magnetron is the type of tube used in all microwave ovens. In spite of the advancing state of the art in power semiconductor technology, the vacuum tube still has reliability and cost advantages for high-frequency RF power generation.

Some tubes, such as magnetrons, traveling-wave tubes, carcinotrons, and klystrons, combine magnetic and electrostatic effects. These are efficient (usually narrow-band) RF generators and still find use in radar, microwave ovens and industrial heating. Traveling-wave tubes (TWTs) are very good amplifiers and are even used in some communications satellites. High-powered klystron amplifier tubes can provide hundreds of kilowatts in the UHF range.

Cathode ray tubes

The cathode ray tube (CRT) is a vacuum tube used particularly for display purposes. Although there are still many televisions and computer monitors using cathode ray tubes, they are rapidly being replaced by flat panel displays whose quality has greatly improved even as their prices drop. This is also true of digital oscilloscopes (based on internal computers and analog to digital converters), although traditional analog scopes (dependent on CRT's) continue to be produced, are economical, and preferred by many technicians. At one time many radios used "magic eye tubes", a specialized sort of CRT used in place of a meter movement to indicate signal strength, or input level in a tape recorder. A modern indicator device, the vacuum fluorescent display (VFD) is also a sort of cathode ray tube.

Gyrotrons or vacuum masers, used to generate high-power millimeter band waves, are magnetic vacuum tubes in which a small relativistic effect, due to the high voltage, is used for bunching the electrons. Gyrotrons can generate very high powers (hundreds of kilowatts). Free electron lasers, used to generate high-power coherent light and even X rays, are highly relativistic vacuum tubes driven by high-energy particle accelerators. Thus these are sorts of cathode ray tubes.

Electron multipliers

A photomultiplier is a phototube whose sensitivity is greatly increased through the use of electron multiplication. This works on the principle of secondary emission, whereby a single electron emitted by the photocathode strikes a special sort of anode known as a dynode causing more electrons to be released from that dynode. Those electrons are accelerated toward another dynode at a higher voltage, releasing more secondary electrons; as many as 15 such stages provide a huge amplification. Despite great advances in solid state photodetectors, the single-photon detection capability of photomultiplier tubes makes this vacuum tube device excel in certain applications. Such a tube can also be used for detection of ionizing radiation as an alternative to the Geiger–Müller tube (itself not an actual vacuum tube). Historically, the image orthicon TV camera tube widely used in television studios prior to the development of modern CCD arrays also used multistage electron multiplication.

For decades, electron-tube designers tried to augment amplifying tubes with electron multipliers in order to increase gain, but these suffered from short life because the material used for the dynodes "poisoned" the tube's hot cathode. (For instance, the interesting RCA 1630 secondary-emission tube was marketed, but did not last.) However, eventually, Philips of the Netherlands developed the EFP60 tube that had a satisfactory lifetime, and was used in at least one product, a laboratory pulse generator. By that time, however, transistors were rapidly improving, making such developments superfluous.

One variant called a "channel electron multiplier" does not use individual dynodes but consists of a curved tube, such as a helix, coated on the inside with material with good secondary emission. One type had a funnel of sorts to capture the secondary electrons. The continuous dynode was resistive, and its ends were connected to enough voltage to create repeated cascades of electrons. The microchannel plate consists of an array of single stage electron multipliers over an image plane; several of these can then be stacked. This can be used, for instance, as an image intensifier in which the discrete channels substitute for focussing.

Tektronix made a high-performance wideband oscilloscope CRT with a channel electron multiplier plate behind the phosphor layer. This plate was a bundled array of a huge number of short individual c.e.m. tubes that accepted a low-current beam and intensified it to provide a display of practical brightness. (The electron optics of the wideband electron gun could not provide enough current to directly excite the phosphor.)

Vacuum tubes in the 21st century

Niche applications

Although vacuum tubes have been largely replaced by solid-state devices in most amplifying, switching, and rectifying applications, there are certain exceptions. In addition to the special functions noted above, tubes still[16] have some niche applications.

Vacuum tubes are much less susceptible than corresponding solid-state components to transient overvoltages, such as mains voltage surges or lightning, or the electromagnetic pulse effect of nuclear explosions. This property kept them in use for certain military applications long after more practical and less expensive solid-state technology was available for the same applications.[2]

Vacuum tubes are still practical alternatives to solid state in generating high power at radio frequencies in applications such as industrial radio frequency heating, particle accelerators, and broadcast transmitters. This is particularly true at microwave frequencies where such devices as the klystron and traveling-wave tube provide amplification at power levels unattainable using current[16] semiconductor devices. The household microwave oven uses a magnetron tube to efficiently generate hundreds of watts of microwave power.

Audiophiles

70 watt tube audio amplifier selling for 2,680 USD[26] in 2011, about 10 times the price of a comparable model using transistors.[27]

Enough people prefer tube sound to make tube amplifiers commercially viable in three areas: musical instrument (guitar) amplifiers, devices used in recording studios, and audiophile equipment.[28][][29] The power output stages of audio amplifiers using tubes include transformers to match the speaker impedance to the higher impedance level of the tube circuit; the use of transformers introduces frequency-dependent phase shifts which limit the amount of negative feedback which can be applied before inducing instability. Solid state power amplifiers, on the other hand, are direct-coupled and apply a high degree of linearisation by negative feedback. The output transformer will affect the amplifier's tone (amplitude at different frequencies) in response to the speaker's impedance, and will affect the character of the amplifier's distortion as it approaches maximum power—the use of less feedback than in a semiconductor amplifier produces more distortion products, but they are characteristic of a gradual change, rather than a sudden onset of saturation as happens with large amounts of feedback. There are companies which specialize in high-priced audio amplifiers using tube technology to serve this market. Beyond the amplifier's output stage, more controversial claims[30] are made in favor of tubes used in signal amplification stages and even for using tubes as power supply rectifiers. Professional systems such as music recording studios and public address systems[*citation needed*] rarely employ tubes in microphone preamplifiers or other applications.

Tube-based electric guitar amplifiers are also preferred to semiconductor equipment by many.[] In this application users are not seeking the most accurate reproduction of an original sound, but rather for the equipment to add its own characteristics. The sound produced by a tube power amplifier when overdriven has defined the texture of some genres of music such as classic rock and blues. Rather than the hard clipping characteristic of solid state power amplifiers, a tube amplifier and output transformer produces audibly different and distinctive distortion. Guitarists often cite the sound of tube amplifiers for the "warmth" of their tone and the natural compression that results when overdriven (as guitar amplifiers routinely are). Also in this same manner, the majority of blues harmonica players also prefer tube driven amplifiers over solid state devices due to this same "warmth", but also because the tubes' natural distortion and low to mid-range frequencies are more favorable to achieve the well-known "dirty harp" sound.

It is difficult to replicate the sound of tube amplification due to the complex nature and non-linear processes of tube amplification. In order to replicate the sound of the fine details and unpredictable nuances of tube amplification, some complex not yet perfected analytic methods must be used. These methods have been attempted and are used when creating solid state tube amplification emulators which are available on the market today. However studies have been conducted considering the perceptual aspects (human listening) of the emulator, and have concluded that the tube sound has not been successfully emulated using digital methods. To the trained ear, the preference of tube sound means that a tube amplifier must be used rather than a digital emulator.[31]

Vacuum fluorescent display

Typical VFD used in a videocassette recorder

A modern display technology using a variation of cathode ray tube is often used in videocassette recorders, DVD players and recorders, microwave oven control panels, and automotive dashboards. Rather than raster scanning, these vacuum fluorescent displays (VFD) switch control grids and anode voltages on and off, for instance, to display discrete characters. The VFD uses phosphor-coated anodes as in other display cathode ray tubes. Because the filaments are in view, they must be operated at temperatures where the filament does not glow visibly. This is possible using more recent cathode technology, and these tubes also operate with quite low anode voltages (often less than 50 volts) unlike cathode ray tubes. Often found in automotive applications, their high brightness allows reading the display in bright daylight. VFD tubes are flat and rectangular, as well as relatively thin. Typical VFD phosphors emit a broad spectrum of greenish-white light, permitting use of color filters, though different phosphors can give other colors even within the same display. The design of these tubes provides a bright glow despite the low energy of the incident electrons. This is because the distance between the cathode and anode is relatively small. (This technology is distinct from fluorescent lighting, which uses a discharge tube.)

Vacuum tubes using field electron emitters

In the early years of the 21st century there has been renewed interest in vacuum tubes, this time with the electron emitter formed on a flat silicon substrate, as in integrated circuit technology. This subject is now called vacuum nanoelectronics.[32] The most common design uses a cold cathode in the form of a large-area field electron source (for example a field emitter array). With these devices, electrons are field-emitted from a large number of closely spaced individual emission sites.

Their claimed advantagesWikipedia:Please clarify include much greater robustness and the ability to provide high power output at low power consumption. Operating on the same principles as traditional tubes, prototype device cathodes have been fabricated in several different ways. Although a common approach is to use a field emitter array, one interesting idea is to etch electrodes to form hinged flaps – similar to the technology used to create the microscopic mirrors used in digital light processing – that are stood upright by an electrostatic chargeWikipedia:Please clarify.

Such integrated microtubes may find application in microwave devices including mobile phones, for Bluetooth and Wi-Fi transmission, in radar and for satellite communication. As of 2012[16] they were being studied for possible applications in field emission display technology, but there were significant production problems.

Patents

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