Introduction to vacuum tubes

1. Operating principles and manufacturing technologies

The operation of electron tubes, also referred to as vacuum tubes, depends upon the current associated to a stream of electrons, negative charged elementary particles, flowing from the surface of an electrode, referred to as cathode, to another electrode, called anode. The emission of electrons takes place from the surface of the **cathode** whenever electrons, under the action of different energy sources, are accelerated above the so called ‘work function’, characteristics for each metal and usually expressed in volts. The type of emission depends upon the source of energy used to accelerate electrons:

- Thermoionic, or primary emission, is the most used in electron tubes and takes place when cathode is heated near to the incandescence. Usually there is a filamentary resistor heated to a temperature going from dull-red to white by a current flowing in it. Alternatively the emitting surface can be heated by other means, as electron or ion bombardment.
- Secondary emission, when high-energy particles strike the cathode surface.
- Phothoelectronic emission, when surface electrons are excited by visible, IR or UV radiations.
- Field emission, when electrons are accelerated at room temperature by intense electric fields.

The cathode base materials and its surface coating if any, as well as the source of heat and the heat transfer to the cathode itself, are selected for optimum operation in each tube type.

In free air emitted electrons are readily blocked by impacts with gas molecules. Anyway they easy travel to a positive anode electrode in high vacuum, resulting in a current flow in the cathode-to-anode space. Vacuum tubes then must have a sort of **hermetic envelope**, carefully evacuated and sealed after the electrodes have been assembled. In some cases a little quantity of gas may be intentionally pumped into the envelope. In these tubes some electrons impact gas molecules, so originating positive charged ions that flow to the cathode and contribute to increase the conduction.

In absence of superimposed electric fields, electrons emitted from the cathode surface originate a dynamic electron cloud all around. The cloud, known as space charge, repels other electrons emitted by the cathode and at the same time gains part of their energy.

Electrons emitted from the cathode are attracted by a positive charged metal plate placed inside the same envelope. In their travel to the **plate** electrons generate a current flow. A very weak current flow to the plate can be observed even in absence of any electric field. This current is generated by electrons escaping the space charge cloud, due to the energy impressed them by the cathode thermal emission. Anyway we will only consider the currents flowing in the vacuum tube when the plate is sufficiently positive with respect to cathode to overcome the repelling effect on electrons by the space charge.

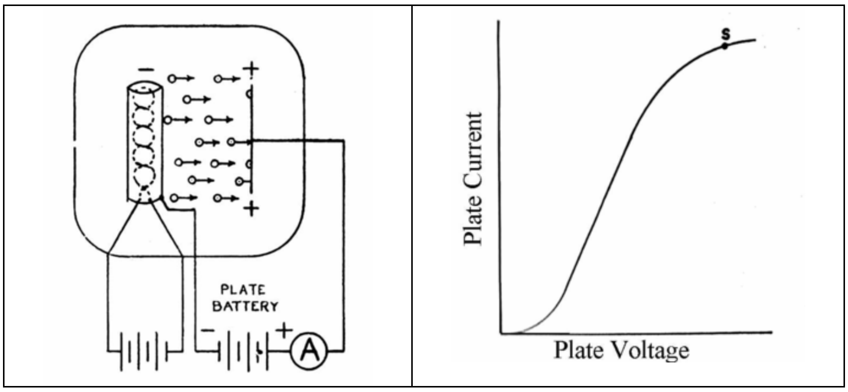


Fig. 1 - A pictorial representation of electrons moving from the cathode cylinder (-) to the plate (+) under the effect of the electric field generated by the plate battery. The double spiral heater inside the cathode supplies the thermal energy needed to accelerate electrons and let some of them to leave the cathode surface. On the right a typical plot of the plate current versus plate voltage. The non-linearity and the offset at very low voltages are due to the presence of the negative space charge, the cloud of free electrons surrounding the cathode, which sums algebraically to the field generated by the plate battery. Quite soon a saturation point S is reached where the current does not increase further, since all emitted electrons are attracted by the anode.

The flow of electrons in their travel from the cathode to the anode, under the influence of a steady electric field applied between these electrodes, can be controlled by superimposed electric or magnetic fields. The grid is the electrode capable of controlling electron flow by electric influence. Usually it is a spiral of very tiny wire placed around the cathode.

Historical notes

Extensive experiments on conduction across electrodes as function of electric fields, gas pressure and temperature were performed by Edmond Becquerel as early as 1853. Since 1880 Edison started to investigate the reason why the bulb of his lamps darkened during operation. To detect the particles that were supposed to be responsible for glass darkening, Edison added a small metal strip in the bulb of some samples. When the plate was connected to the positive terminal of the filament, he noted a current flow from the filament to the metal plate proportional to the degree of incandescence, or the temperature, of the filament. He concluded that carbon particles moved toward the glass under the action of negative charges, later known as electrons. The so called ‘Edison effect’, that was the forerunner of thermoionic emission in vacuum tubes, was then thoroughly investigated even in other countries, mainly to increase the efficiency of light bulbs. In November 1883 Edison applied for a patent on an ‘Electrical Indicator’, a lamp capable of giving remote indication of its operation, just monitoring the current flowing to a metal strip added in the bulb.

John Ambrose Fleming ran further experiments, even using alternate currents, on Edison effect when working at the Edison Electric Light Company of London. In 1899 Fleming became technical advisor for the Marconi Wireless Telegraph Company. Looking for a sensitive detector of radio signals he successfully tried the lamps used for his experiments on the Edison effect. He called the device ‘oscillation valve’ and patents in Great Britain, U.S. and Germany were filed between 1904 and 1905. This can be considered the first use of a thermoionic vacuum tube and the beginning of the electronic science.

The next step was to investigate devices in which a signal could control the electron flow, capable of operation either as amplifiers or as oscillators. Small quantities of gas inside the envelope, often due to poor vacuum pumps available, were also proposed to increase the sensitivity of some devices when used as detectors, biased close to the ionization threshold. Several ways were tried to make the signal to interact with electrons, even from the outside of the evacuated glass bulb. Lee de Forest in 1908 patented his three electrode valve, later known as triode. In the triode a wire bent back and forth to form a sort of gridiron, hence the grid, was placed between the filamentary cathode and the anode. This solution was by far the most accepted one. Anyway a mention goes also the oscillator tube patented in 1912 by Robert Goddard, the rocket pioneer, followed by the production of some unconventional tubes many years later, the C100A and the C100D, made for Collins.

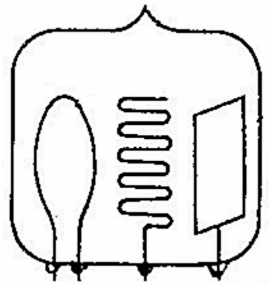


Fig. 2 - Drawing of the early Audion triode, from the De Forest patent. Starting from the left, the filamentary cathode, the grid and the plate.

Early tubes used filamentary direct-heating cathodes. In many transmitting and high-power tubes tungsten or thoriated-tungsten filaments were retained. Oxide coated filaments were soon preferred in receiving and low-power tube types, due to their higher efficiency which made possible operation at lower temperatures. We must wait until 1925 to see the first indirectly heated cathode, capable of hum-free operation when AC supply sources were used. In the early unipotential cathode tubes introduced by McCullough heater came out from top of the glass bulb.

In the twenties we see a parallel growth of AM radio broadcast services and of vacuum tubes, including high-power transmitting types. New materials were investigated and more efficient processes were found to increase performances and yields of vacuum tubes even reducing their costs.

Vacuum tube classification

When talking of vacuum tubes, usually we just think of the radio receiving types. But vacuum tubes were designed in the past century to fill almost any field of human activity. The huge variety of devices introduced in the years by tube manufacturers makes very difficult to select uniform criteria for their classification, size or type of bulb, external connections, number of electrodes, type of cathode, power, function, principle of operation, application. A first classification could just separate high-vacuum devices from gas-filled types.

Another coarse classification could consider the application for which the tube was designed, even if boundaries are not sharply defined:

- Radio reception, includes tubes designed for radio and/or television sets
- Radio transmission, with power tubes for AM/FM/TV broadcast transmitters
- Radar, including many special tubes designed for radar systems.
- Industrial, including power tubes used in RF heating, welding and anyway in process control
- Computers, with tubes intended both for analog computing and for logic and interface circuits
- Measurement, with transducers and signal processing tubes
- Military and Aerospace, with tubes designed for reliable operation in extreme environments.
- Display, with CRT tubes and similar devices
- Electro-medical, including X-ray tubes
- Power conversion, including tubes designed for power supply circuits

The classification given above may be expanded to include other tube families and even glass-sealed passive components.

Mainly for receiving tubes another classification could take into account the number of electrodes, as in the table below.

Number of electrodes	**Type name**
2 - cathode and anode	Diode
3 - cathode, grid and anode	Triode
4 - cathode, two grids and anode	Tetrode
5 - cathode, three grids and anode	Penthode
5 - cathode, two grids, beam forming grid and anode	Beam tetrode
6 - Cathode, four grids and anode	Exode
7 - Cathode, five grids and anode	Pentagrid or Heptode
8 - Cathode, six grids and anode	Octode
9 - Multiple units, e.g. diode-triode or twin-triode	

Referring to the source of electrons we can assume the following classification:

- Cold cathode, as in some gas-filled tubes
- Directly heated or filamentary cathode. Filament can be coated with oxides for increased efficiency.
- Indirectly heated or unipotential cathode, usually a cylinder of nickel alloy coated with oxides and containing a resistive wire as heater.
- Cathode heated or assisted by ion bombardment, used in some gas-filled rectifiers.
- Cathode heated by electron bombardment, used in some high-power tubes.
- Secondary emission cathode, operating at ambient temperature, in which impact of electrons on a treated surface frees other electrons.
- Photocathode, in which electrons are emitted under the effect of light.
- Virtual cathode, when electrons of a normal cathode are accelerated and deflected to start their operative travel from a virtual origin.

Power and high-power tubes may also be classified according to the way they dissipate heat. For better heat transfer the anode is external over about 1 kW or even less for compact types. We can define the following basic families:

- Radiation and convection through the glass bulb, for power up to about 500 W, as in fig. 3-A.
- Conduction cooled, used in some external-anode power tubes, fig. 3-B
- Forced-air cooled, for power up to about 10 kW. Usually a finned radiator is brazed to the external anode, fig. 3-C
- Water, vapor or liquid cooled external anode, for power over 1 kW, fig. 3-D
- Oil immersion, mainly used for tubes operating at high-voltage, fig. 3-E

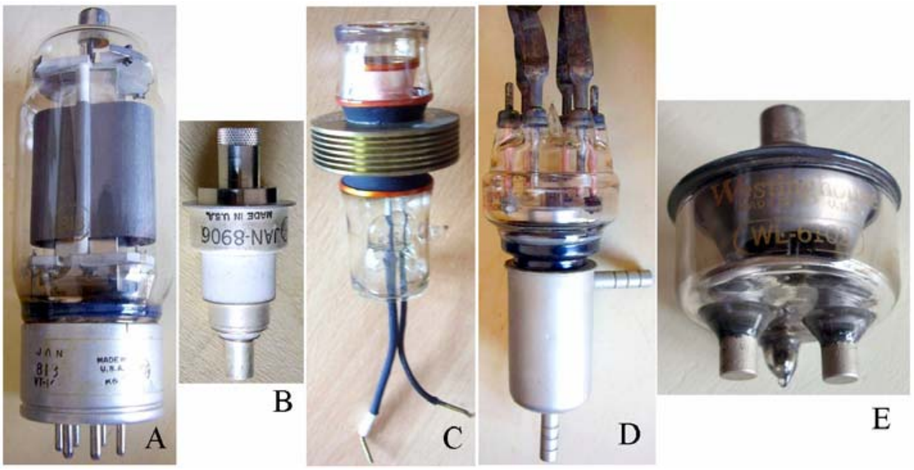


Fig. 3 - Examples of different power tube types with respect to their cooling. From left, free-air convection, conduction, forced-air cooling, water cooling, oil immersion.

Other criteria for classifying most of the amplifying and oscillating tubes could take into account their frequency range. Shapes and even the same operating principles vary considerably for frequencies over some tens megahertz.

The border line between the same receiving and transmitting tubes can be just a matter of application for several small tubes. Audio power amplifiers, as 6F6 or 6L6, were commonly used as transmitter tubes up to some 60 MHz. In microwave relays the same tube, a disc sealed triode or a klystron, was used as transmitter, to generate the needed watts of RF power, and as local oscillator in the superheterodyne receiver. Low-power microwave tubes, as the acorn triode 955, were used in pulsed beacon or radar transmitters to generate relatively high power pulses at low duty cycle.

In our catalog we divided exhibits in 12 major families, some including two or more subfamilies. Other families were added to list tubes by a few manufacturers. Due to multiple applications of some tubes, in our survey we can find some types listed in more than one family.

Notes on tube design

Most of the available documentation on vacuum tubes talks of receiving types, focusing on their theory of operation. Constructive details were the assets of the manufacturers, involving advanced researches in many scientific disciplines, and were carefully secreted. Serious tube manufacturers had their own laboratories of chemistry, matter physics, optics, metallurgy and vacuum physics. Parallel researches were performed in the most prestigious universities. All evolved in the years, as result of the search for tubes capable of improved performances. New tube shapes asked for painstaking works in defining suitable materials, glass compositions, tooling, processes and test tools. The simple operations for manufacturing, spraying and activating the cathodes for a new computer-rated tube, the preparation of the alkaline-earth carbonate precipitations, the ball-milling of the crystals to the proper particle size and the subsequent washing, the preparation of the coating solution and the settings of the spray-gun aperture and distance, up to the parameters of the oxide activation process, all the information were safely stored by production responsibles.

The evolutions over the years of materials, tools, processes and testing for long lasting tubes can only be guessed when carefully comparing datasheets of the same tube type printed at different dates and by different manufacturers. We will shortly examine some details of the basic components of vacuum tubes to understand how even two tubes of the same type could be different from each other.

Tube envelope

Electrodes must operate in the vacuum or anyway in a controlled gaseous atmosphere. A relevant role is then performed by envelope. It must be hermetic, capable of withstanding high operating temperatures and must exhibit good insulating properties, at least where electrodes are connected to the outside. The most common envelopes, at least for receiving tubes, are made of glass or metal-glass. In the most popular metal tubes the envelope was made of ‘fernico’ alloy, iron-nickel-cobalt, its base fitted with glass beads or with a single glass button, with sealed lead wires or pins inside. The very early commercial metal tubes were the so called ‘catkins’, introduced by British GEC around 1931. CAT was the prefix of GEC external anode transmitting tubes and stays for ‘Cooled Anode Transmitter’. General Electric and RCA introduced their metal octal tubes few years later, starting from 1934.

Glass bulbs were widely used even for medium power industrial and transmitting tubes. Heat exchange through the glass is poor and darkened radiating surfaces were needed for plates. The bulb itself must operate at very high temperature and special glasses were developed. At plate power over few watts bulbs were usually made of heat-resistant glass, as nonex or pyrex. For a while before WWII British used fused quartz for their ‘silica valves’, as the CV14, the NT45A, the NT57D, the NT57T and the TYS5-2000, in the collection.

Over about 1 kW heat must be directly transferred from anode to outside. Copper was commonly used in external anode tubes and anode was sealed to glass domes or spacers supporting other electrodes. Glass must anyway withstand high operating temperatures and sometimes an appreciable electron bombardment without softening. Moreover it must have a thermal expansion coefficient close to the one of the anode material and of the electrode connecting rods, otherwise seals will crack. Then the need to find proper glasses for each metal or metal alloy used for anode and for electrode connections and to define the proper sealing procedures. Other important aspects to consider when choosing the proper glass for each application could be:

- optical properties, in CRTs and imaging tubes
- ability to resist electrolysis effects, particularly in high-voltage tubes
- resistance to punctures due to electrical losses, both DC and microwave
- surface conduction, of paramount importance in electrometer amplifiers
- X-ray absorption, in tubes operating over some 20 kV

The vacuum tube industry developed countless solutions for electrodes and their connection to the outside and consequently also developed many and many glass compositions. Today that science is dead, but in the mid fifties a single glass supplier, Corning Glass Works, listed some thirty commercial types just for vacuum tubes.

Glass powders had to be handled by master glassmakers by far more skilled than those of Murano. They were capable of building complex yet precise glass structures, sealing them to other glass pieces and to almost any metal, as in the tube below.

Fig. 4 - A very complex glass masterpiece with six radial spokes, sealed to heavy metal fed-throughs. The glass dome is then sealed to the copper anode below and evacuated from the top. Philips TAL-12/35.

Fig. 5 - Other complex glass structures in high frequency tubes. Here high temperature glasses are precisely formed, assembled and sealed to very close tolerances, assuming a true structural function in supporting and spacing internal electrodes.

Around the mid fifties ceramic materials, such as alumina or later beryllia, started to replace glass in many power and microwave tubes. In high power applications, ceramics were superior to glass, stable and capable of safe operation at high temperatures. New processes were developed to mold and work to final shape alumina before firing it and to metallize the surfaces to be brazed to other metal parts.

Even in this case the development of new materials and technologies lead to the introduction of other ceramic compounds, as forsterite and berilla, and of a variety of sealing compounds. The same design of tubes evolved to a sandwich made of metal discs or rods, each terminating an internal electrode, sealed to ceramic spacers.

Fig. 6 - Due to the exceptional stability of ceramic materials used as spacers beteen electrodes, small triodes were made, capable of reliable operation up to about 10 GHz in extreme environmental conditions, up to 400ºC, and even in strong radiation fields. 7077, the second sample from left, was used in the Pioneer space probe. About 2x actual size. Here the GE Notes on these tubes.

Cathodes

The cathode is the source of electrons. We usually refer to primary emission or thermoionic cathodes, by far the most used in vacuum or gas-filled tubes. The very early source of electrons was a filament heated to white light, like in a lamp. Electronic theories had still to come and the emission was called ‘Edison effect’. Since 1903 Wehnelt had observed that alkaline-earth oxide surfaces were more efficient sources of electrons, granting plenty of electrons at relatively low temperatures, about at dull-red. From the early 1920s most of the vacuum tube manufacturers introduced high-efficiency oxide coated filamentary cathodes. The well known ‘Miniwatt’ series by Philips made its first appearance in 1923.

Early radio sets usually operated from battery supplies. With the diffusion of AC power distribution, we see in 1925 the early tubes with indirectly heated cathode, capable of hum-free operation. Among the first tubes introduced by McCullough, heater connections being terminated on the top, to facilitate the conversion of existing radios. Early indirectly heated triodes used a hairpin tungsten wire fitted into a porcelain spacer inside a nickel tubing. They were characterized by poor efficiency and warm-up period in the order of minutes: C401 required more than 1 ampere at about 3 volts to operate. Very soon indirectly heated cathodes were improved with the introduction of very thin nickel tube walls and thin alumina insulating layer over the heating wire. Heaters took the shapes given below.

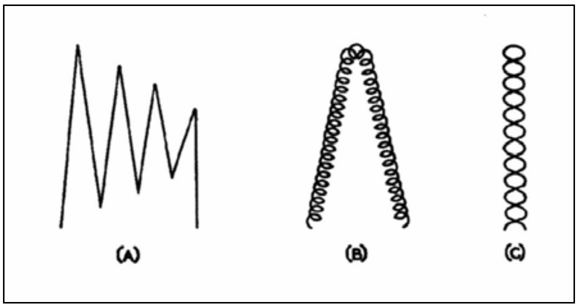


Fig. 7 - Common shapes of heaters: folded (A), helix (B) and double or reverse helix (C). The latter is preferred to reduce hum in low-level amplifiers. The folded shape, made starting from drag-coated wire, was by far the most used in receiving tubes. The helix heater, cataphoretically coated, was preferred in high-rel tubes. Double helix was preferred in low-hum audio and instrumentation amplifier tubes.

Heaters and heater power were specified and designed according to the wanted emission and to the specific application of some tubes. For a given power, being heaters just resistive elements, manufacturers specified a couple of nominal figures, voltage and current. Of course a certain standardization took place at least for receiving and low-power tubes. Common voltages for tubes intended to be operated with parallel heaters were 6.3 and 12.6 volts. These values were probably selected as corresponding to average voltages of three and six elements lead batteries. In many low cost radio and television sets heaters were connected in series, so eliminating the need for power transformer. In these cases we usually find heaters specified for current values of 150, 175, 300, 450, 600 and 1200 mA or even greater, depending upon the required emission. Anyway we see different design rules between US and European manufacturers.

Voltage ratings of tubes specifically designed for series operation of heaters is related to the nominal current, so to operate at constant power, usually 1.9 W (300 mA at 6.3 V) for most low-level receiving types. Then we see that 3AU6 is rated for 3.15 V at 600 mA, 4AU6 for 4.2 V at 450 mA, 6AU6A for 6.3 V at 300 mA and 12AU6A for 12.6 V at 150 mA. Of course nominal current was influenced by how many of tubes were to be used in a given set and by total heater power required. We can assume 1.9 W average power for each low-power tube and about 4.5 W for each power type.

The American power distribution was standardized at 117 V. For a radio set using four low-power tubes and two power types, audio amplifier and rectifier, we have a total heater requirement around 17 W, corresponding to a current of about 150 mA. For an 18-tube television set we could assume a total heater power of about 50 W, corresponding to a current of about 450 mA at the same voltage.

In Europe we find different current values specified, probably related to the 220 V power distribution systems commonly in use. Here in Europe we find families with lower current heaters, as the 100 mA (U) for radio or the 300 mA (P) for TV sets.

Another difference derives from the coding system. In Europe the first letter identifies either the voltage or the current ratings. Some letters identify tubes designed for series connected heaters, as H (150 mA), P (300 mA) or U (100 mA), other letters identify tubes designed to operate at certain standardized voltage values, E (6.3 V), G (5 V). Here some examples:

Type	Ratings I or V	Notes
EF85	6.3 V	Parallel or series operation, 300 mA
EF89	6.3 V	Parallel operation, 200 mA
EF94	6.3 V	Mazda, 300 mA parallel
EF94	6.3 V	Lorenz, 300 mA, series/parallel
ECC82	6.3 V (or 12.6 V)	Parallel/series, 300 mA (or 150 mA)
HF93	150 mA	Series operation, 12.6 V
PF86	300 mA	Series operation, 4.5 V
PL36	300 mA	Series operation, 25 V
UF89	100 mA	Series operation, 12.6V

The rigid application of this system led to some inconsistencies. Of course the heaters of tubes as HF93 or UF89 can be parallel connected, powered from 12.6 volts sources, but the parallel supply is not even mentioned in many datasheets in an obstinate compliance with coding rules. The EF94 from Mazda-Belvue in a datasheet dated 1968 is specified only for parallel operation, while in 1953 Lorenz specifies the

EF94 for series or parallel connection, even if the insulation from heater to cathode was as low as 50 V.

American RMA stated a more serious system to identify heaters designed for reliable series connection. The code of receiving tubes always starts with a figure of one, two or even three digits, which approximates the voltage rating of the heater. The possible use of heater in series strings is specified by another parameter, the heater warm-up time. By definition this is the time required for heater to develop 80 per cent of the rated voltage, after the power has been applied through a series connected resistor. Controlled warm-up prevents excessive heater voltage buildup at power-on across the faster-heating tubes. Here some examples:

Type	Ratings I or V	Notes
4AU6*	4.2 V @ 450 mA	Series supply, 11s warm-up
6AU6	6.3 V @ 300 mA	Parallel heater supply
6AU6A*	6.3 V @ 300 mA	Parallel/series supply, 11s warm-up
6J6	6.3 V @ 450 mA	Parallel supply
6J6A*	6.3 V @ 450 mA	Parallel/series supply, 11s warm-up
12AU6	12.6 V @ 150 mA	Parallel supply
12AU6A*	12.6 V @ 150 mA	Parallel/series supply, 11s warm-up

Note: asterisk identifies controlled warm-up heaters.

Other parameters usually specified are the maximum voltage allowed between heater and cathode and sometimes the insulation resistance. Even maximum allowable DC biases, positive or negative, can be specified in some cases. This because of electrolysis which can take place through the heater coating at high temperature.

The cathode assembly was similar to the one below, with a nickel sleeve coated by the oxide layer and the heater inside.

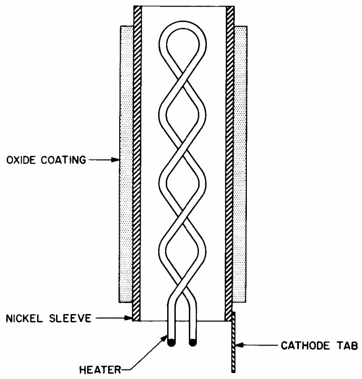


Fig. 8 - Typical indirectly heated unipotential cathode assembly. The twin-helix heater winding was used in low-level tubes specified for low-hum.

The tungsten or tungsten-molybdenum (Dowmo or J wire) heater was insulated with a thin coating of alumina by several drag-layer steps or by cathaphoretic processes, using a suspension of alumina particles. The selection of the proper alloy for the cathode sleeve and the successive processes to obtain a uniform coating of rare-earths oxides were then among the most critical steps in manufacturing vacuum tubes. As said before, rare-earths oxides were excellent sources, capable of supplying plenty of electrons at relatively low temperatures, around 1000 K. Anyway oxides had to be activated with migration of reducing agents from the underlying nickel alloy and the consequent release of excess barium. Emission is influenced by the dynamic equilibrium of barium at normal operating temperature. Once activated with the formation of an interface layer between the sleeve and the oxide, the cathode acts as a semiconductor with free atoms of barium, donors capable of supplying electrons, uniformly distributed within the oxide layer.

The design and the manufacturing of oxide-coated cathodes, up to their activation during the vacuum tube seal-off phase, was a true art. Once defined the design parameters, power, temperature, size or surface and current density, the entire manufacturing process was extremely critical, influenced by the selection of materials, by their purity and processing, by temperatures and reaction timings for each step. An impurity or a non uniform movement of the gun when spraying the nickel sleeves with barium carbonate could result in a poor emission or in a thick layer which could easily peel off. And even in a well processed tube the emitting surface could be quickly destroyed by occasional overheat.

Cathode processes varied considerably even depending upon the specific applications of each given tube type. To accelerate the activation process and even to extend the useful life, small quantities of silicon were added to the sleeve nickel alloy in most of the receiving tubes. Unfortunately at high temperature silicon reacts with barium oxide to form barium orthosilicate, an insulating compound which lowers the temperature of the emitting surface and increases the interface impedance. The build-up of such impedance was found to prevent the instantaneous emission in tubes used in pulsed or logic circuits, after long period in standby condition. Lower interface impedance was obtained using passive nickel alloys, but in this case longer and more complex activation process was required. In power receiving tubes silicon doping in the cathode sleeve over about 0.20 per cent was even found to cause excessive barium evaporation and subsequent grid emission.

Things were even more complex with cathodes of special tubes. In the case of tubes intended for pulsed operations, as radar magnetrons, special cathodes were devised made of sintered nickel or tungsten pressed on the outer surface of a molybdenum sleeve and then cataphoretically filled with barium carbonate. Porous surfaces increased the emitting surface also acting as shield against impact of high energy positive ions. Emission levels of some tens amperes per square centimeter and life expectancy in the order of thousands hours were attainable. In the picture below we see two different versions of the cathode assembly in the 725A magnetron.

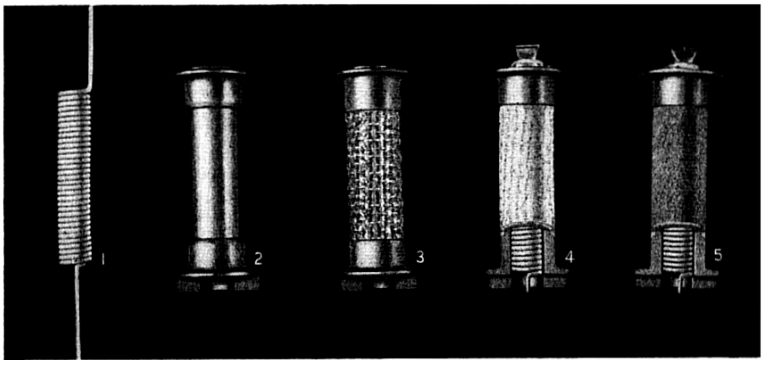


Fig. 9 - 1 to 4, four images of an early cathode assembly of 725A magnetron. The nickel mesh welded over the machined nickel tube is then impregnated with oxides. The nickel mesh increases the emitting surface, also protecting oxides from direct bombardment by high-speed particles. The cathode in 5, still uncovered, is made with sintered nickel powder on a matrix base.

Looking at the ultra-reliable amplifiers for transatlantic repeaters, the 175HQ and the 455A, we find information on how their cathode assemblies were designed for stable operation over an expected life span of twenty years. Very low operating temperature and the widest practical surface were specified for these tubes. A comprehensive article is given in the Bell System Technical Journal, January 1957.

A very special cathode was devised for some expensive high-power transmitting tubes, based upon heating by electron bombardment. Oxide coated cathodes are not suitable for operation at high-voltage, since oxides are readily destroyed by positive ions accelerated by the same electric field. One of the finest solutions used a tantalum sheet as emitting surface and even as getter. Tantalum was heated by back-bombardment of electrons emitted from a tungsten wire cathode placed behind, in a separate chamber. This solution offered a stable and nearly infinite life of the tube, in the order of 10,000 hours. In case of failure of the tungsten filament, the same could easily be replaced without opening the main vacuum chamber. The full article, edited by the engineering staff of Varian, was given in Electronics, October 1951.

The heater-to-cathode insulation was another issue which evolved in the years, with new applications or openings to new markets. Let us examine successive releases of documentation for a common receiving tube, as the 6AU6. This sharp-cutoff pentode was developed by RCA during WWII for military applications. Later and for over than thirty years it was manufactured worldwide and found countless uses, including instrumentation and television sets.

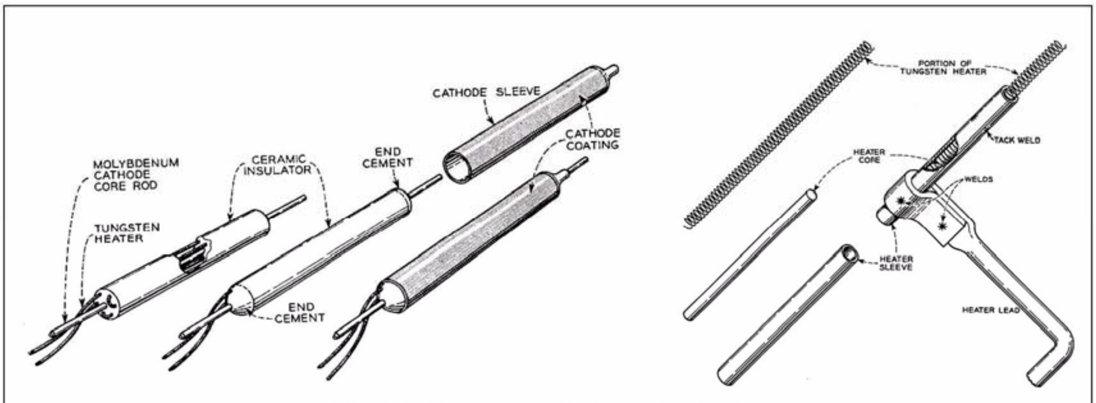
In RMA record 446 we find a value of ±90 volts specified by RCA in its first release, October 1945. RCA raised the insulation to -180, +100 volts in the release C, June 1951, and raised it again to ±200 volts in the release G in January 1960. But already in June 1956 General Electric had registered the 6AU6A, specially designed for television sets with string connected heaters, specifying ±200 volts heater-to-cathode insulation and controlled warm-up time. Looking at the figures given by other manufacturers for the same tube, we find remarkable differences. In 1959 Sylvania gave +100V / -200V insulation for both its 6AU6 and 6AU6A. As seen above, in

Europe Lorenz specified as little as 50 V for its equivalent EF94, with a mere 10 kohms insulation resistance, but we must remember that at the time very few German sets used series connected heaters. Mazda-Belvu specified 180 V for its dual coded 6AU6/EF94. We find -180, +100 volts in 1958 for Italian Marconi 6AU6 and only 100 volts for Mullard. We also find a surprisingly high value, 250 volts, for British Brimar in 1949. Probably some of its customers planned to use this tube in sets with string heaters at 220 V. This survey does not consider data for high-rel variants of the same tube, 6136, 7543 and 8425A. Of course we must expect a relevant influence of the heater-to-cathode insulation even upon other aspects, as hum or DC leakage.

As for other aspects in the production of vacuum tubes, just slightly deepening our knowledge of processes that lead to the production of simple cathodes, we can realize why tubes of the same type usually differ from one another even considerably. The reasons can be summarized as follows:

- Different designs, materials and processes used by each manufacturer at any given date.
- Different materials and processes used by the same manufacturer in the years.
- Different tests and/or screenings through the years.

We can only guess that each tube manufacturer offered in the years the specs that its top customers were asking for. Anyway we easily see how different could be tubes coming from different tube suppliers or even from different lots. This is the reason why manufacturers of high performance electronic sets often handled tube replacements as custom parts through their own service departments, screening each tube for critical parameters.



Cathode-heater assembly and heater wire termination

Fig. 10 - The cathode-heater assembly of the Bell 175-HQ high-rel amplifier for submarine repeaters.

Grids

Control grid, and other grids when present, are electrodes capable of controlling the distribution of the electric field and hence the electron flow in the space between cathode and plate. Readers can consult the wide literature existing on the theory of operation of gridded tubes. We will focus on some little known constructive aspects which differentiate various tubes according to their specific applications.

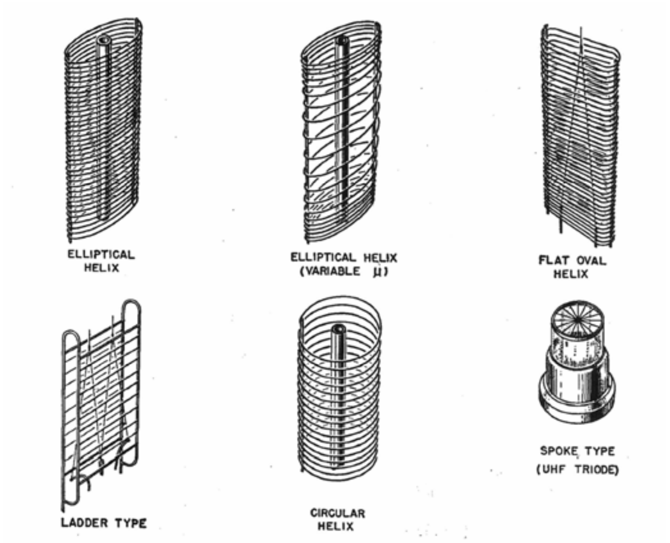


Fig. 11 - Typical examples of control grids used in receiving and small transmitting tubes.

Most of the grids were made of fine wire wounded on rigid side rods. But special designs were developed for UHF and power tubes. Here we see some special grids:

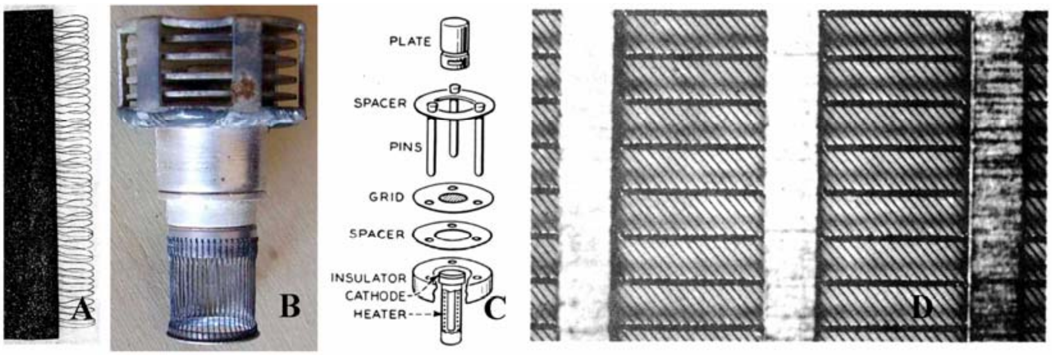


Fig. 12 - A, small tungsten loops welded to a cooling fin were used in UHF doorknob tubes as 316A, circa 1936. B, a parrot-cage grid made of molybdenum or tantalum wires, welded all around the circumference of the grid support rod, was used in the micropup tubes, as the 3C37, early 1940s. Planar or disc-seal triodes used a wire mesh welded or brazed to a copper disc. In C the components of an early prototype of WE 416A. In D the grid is formed by extremely tiny wires, 0.3 mils (about 0.00077 mm), diagonally brazed to vertical and smaller horizontal bars, photo-etched in the grid disk. Precision grids of such type were used in the small ceramic GE triodes, capable of operation up to about 10 GHz, as the 7077. About 1960.

In high perveance high-frequency tubes the spacing from the grid to the cathode surface was very small. The grid wire was directly exposed to the high temperature coming from the cathode itself. Grid currents, when grid goes positive in class C or pulsed operation contribute to overheat the tiny wires and primary emission could take place from them. To prevent emission in many power tubes, as 701A or 715A, grid wires were gold plated, wire being supported by heavy rods of high-conductivity materials. Special radiating fins were sometimes used to terminate the grid supports. The grid assembly of figure 12B above was terminated outside the bulb in the visible finned radiator, cooled by forced-air flow. The drawback of gold coating was its relatively low evaporation temperature, around 700ºC. Grid overheating above this value caused a rapid buildup of primary emission and poisoning of the cathode surface by gold.

Some grid coating processes originated another trouble, the so called ‘blackout’. Occasionally receiving tubes in the radar front-end were found dead for a while to incoming signals after that the grid had been driven positive during the transmitted pulses. In this case a semi-insulating layer was found deposited on the surface of the grid wire. This layer acted as the dielectric of a capacitor formed by the grid wire and the external surface, where electrons accumulated during the pulses, and the tube retained an undesired self-bias, until the discharge of such a capacitor.

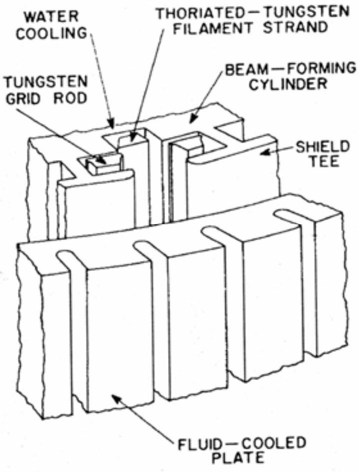


Fig. 13 - Many high-power triodes used a ‘shielded grid’ design to prevent secondary emission caused by grid overheating, The above solution, with grid rods placed inside groves of a beam-forming cylinder to operate in a ‘gammatron’ mode, recalls the operation of a field effect transistor.

Plates

Plates collect electrons and must be capable of dissipating heat caused by electron bombardment and also by cathode radiation. Materials must have good electrical conduction properties and must be capable of radiating the generated heat or transferring it by conduction to suitable radiators. Moreover, due to their relevant surfaces, materials must be selected for low gas content and for low tendency to oxidation during manufacturing steps. Shapes can be quite different from each other, depending upon the application and even upon the need of transferring heat to outside. In many high-power or high-frequency tubes plate conducts heat directly to outside, also acting as part of the evacuated envelope. The most complex shapes also include the same resonating circuits, as in many magnetrons or in the Resnatron.

Highest efficiency usually requires good reflection inside and good radiation from outside surface. Common base materials include nickel, aluminum and clad steel, coated with various combinations of nickel and aluminum. Higher power dissipation could be handled using multi-layer materials. A copper layer, with high thermal conduction, was covered by aluminum or clad steel on each side. Copper-cored Aliron, used in some power tubes, was a five-layer material with copper inside, covered on both sides by aluminum-clad steel. For improved radiation cooling plate surface was carbonized and, due to the improved heat dissipation, more heater power was required to reach the proper operating temperature over the cathode surface, unless the inside surface was someway reflective.

Fig.14 - Early power triodes with nickel plates, 1920 to 1930.

As power increases in convection-cooled tubes the plate surface temperature can rise to values between 400º and 1,000ºC, well over the capabilities of common materials. Slightly higher power can be handled using graphite plates, which exhibit good radiation capabilities and can operate up to 700ºC. Graphite is rather fragile and cannot be used where severe vibrations or mechanical shocks are expected.

Fig. 15 - Graphite plates in transmitting tubes up to 500 W.

Power levels even higher are handled by radiation-cooled plates made of molybdenum or tantalum. The last can operate well over 1,000ºC and has excellent radiating properties. Tantalum is also capable of adsorbing residual gases, acting as a very effective getter, when heated to red color. For their properties tantalum plates were widely used in many VHF or UHF power tubes, usually characterized by small electrode size, plate being operated at dull or cherry red temperature.

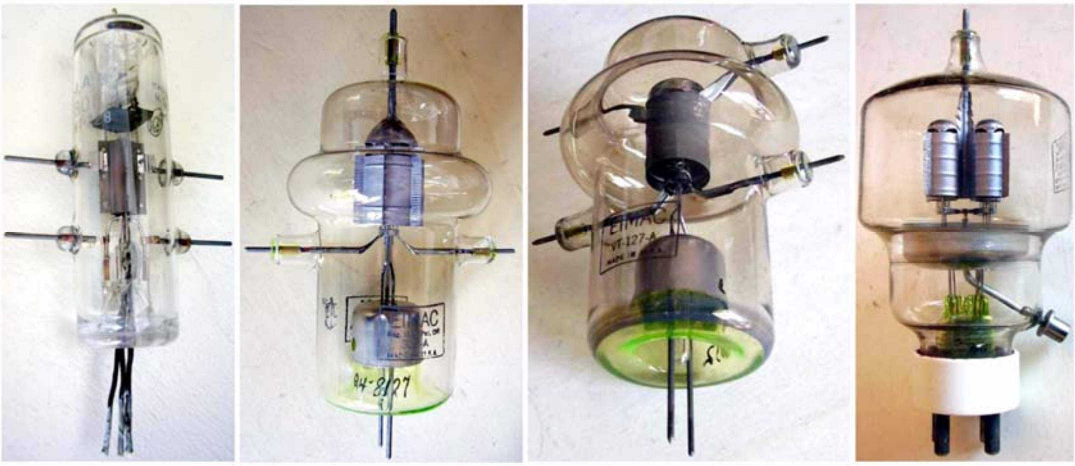


Fig. 16 - Tantalum plates operating at cherry red were common in high-performance UHF power tubes, generally used in VHF radar transmitters. The last tube, with four electrode subassemblies connected in parallel, was used as pulse modulator.

In the most powerful tubes anode is external and heat is transferred by direct conduction to efficient cooling systems which use either forced-air or liquid flow. Copper was widely used in the manufacture of external anodes. Due to its high thermal expansion different from that of glass, special glasses were introduced, as well as special sealing processes, as the feather-edge one devised by Housekeeper.

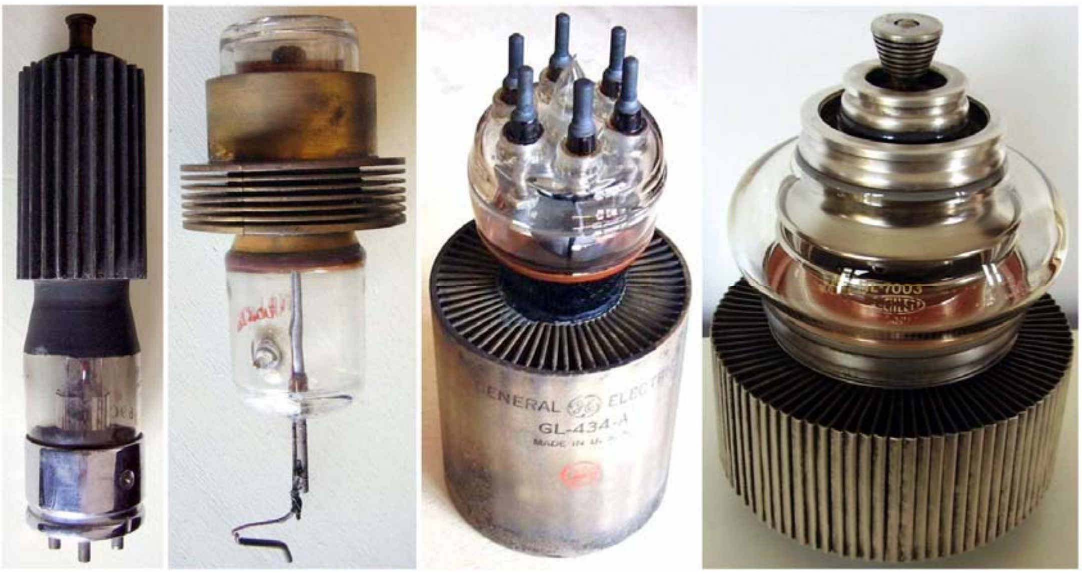


Fig. 17 - Power tubes with air-cooled external anode made of copper sealed to the glass bulb. Radiating fins are brazed to the copper surface.

Fig. 18 - In this case the anode copper block is brazed to the internal wall of the brass finned radiator ring.

Fig. 19 - Water-cooled tubes. Top-left, a small VHF tube with integral heat exchanger. Bottom-left 5J29, a split-anode magnetron fluid-cooled through the anode pins and the internal tuning loop. Other tubes are high power types in which copper anode is cooled by an external water jacket.

In Great Britain fused silica was used by Mullard until 1940 for the envelopes of high-power transmitting tubes. The so called ‘silica valves’ were operated at very high plate temperature.

Fig. 20 - A TYS5-2000 silica valve.

Other materials, as tantalum or molybdenum, were used more recently, even coupled with ceramic materials for the tube body.

Fig. 21 - Cermet power tubes are very compact and rugged.

2. The tube collection

Purpose of the collection is to show the evolution of the electronic science through the years, looking at the evolution of its basic components, the vacuum tube. The most relevant part of the collection spreads over any kind of special purpose types introduced from the late thirties to the sixties. This because of the incredible impulse that communication, navigation, radar and electronic warfare given to electronics by the outbreak of the war, impulse that continued in the subsequent years. British and American types were preferred for ease of finding and reading datasheets and technical documentation. Also preferred were tubes with glass envelopes, for the relative ease to look at internal construction details. What is impressing also for the prophane is the enormous variety of shapes and of sizes. The catalog is divided in sections, to better compare different characteristics and shapes inside each family. Each tube card contains some photos and a short summary of the tube characteristics. Whenever possible documentation and papers are added, in the attempt to give available information, including introduction years and intended applications. In some cases, the tube is also linked to some sets in which it was used.

The collection starts with some very early vacuum tubes. This section is intended to give those initial references to which compare later types. It includes both receiving and transmitting types, from the Great War to the early thirties.

Other sections include types representatives of the various families, power supply, transmitting, high-frequency, microwave and radar related tubes. This latest family includes several rare samples of the early development in England, in America and in Canada. Among the others, samples of E-1189 prototype and production types, NT98C, REL 3C and 3D, of ‘Sutton tube’ prototype and of NR89 very early klystron, as well as samples of early S and X band tubes designed in America. Also present are overviews of electronic sensors, of electrometer tubes, of computer related and counting tubes. We also find samples of radiation sources and of CRTs. The section related to special tubes includes some ultra-reliable types, designed to operate continuously for many years in submarine repeaters. The latest section lists vacuum-sealed electro-mechanical devices and crystal resonators.

The tube collection, along with few examples of complete sets, well gives a significative overview of the progress over few decades of electronics, not asking for excessive room. Furthermore the tube catalog helps to better understand the operation of those sets in which special tubes were used.

Go to the ‘Tube List’.