


# VIVE LES VALVES!

**We call them valves, the Americans call them tubes — whatever you call them, their significance in the history of electronics cannot be underestimated. By Rae Jon.**

Call them "valves", the more sentimental "bottles", the American term "vacuum tubes", "electron tubes" or whatever you wish, they collectively ushered in the age of electronics.

All the tricks of radio reception, transmitters, amplitude modulation, frequency and phase modulation, frequency-shift-keying, pulse and other forms of modulation and demodulation, radar, TV, VHF and UHF, phase-locked-loops, hi-fi audio amplifiers, negative feedback, timers, operational amplifiers, integrators, oscilloscopes, tape-recording and playback, video amplifiers, regulated power supplies, opto-couplers, light modulation systems, electron-multipliers, radioactivity detectors, analogue computers, even the beginnings of digital computers were born and nurtured using the now despised valve.

## Valve history

All humans yearn to know their roots and we, the modern electronic bods, can benefit by looking back into the origins of the circuit configurations and design philosophies developed in the valve environment of the past.

The valves, transistors, FETs or whatever are simply instruments for regulating the circuit current. It is the circuit which holds the secrets. Thomas Alva Edison, the "wizard of Menlo Park", found in 1885 that charged particles are emitted from a hot filament in an evacuated space such as within a vacuum electric lamp. He discovered that a hot lamp filament always loses any negative charge placed upon it. Edison noted this effect in his diaries and that these particles were attracted to a positively charged plate placed within the lamp, but foresaw no useful applications. What an opportunity missed!

It remained for other scientists such as Richardson, Du Bridge and Fleming to apply the principles of physics to the phenomenon and pursue it with serious scientific research. Richardson called the particles "thermions", for thermally-emitted charged ions. He found they could be attracted by any positive electric field nearby. Following a liquid-gas analogy, it was said that particles were "evaporating" from the hot wire. Richardson used the word "thermionics" applying to all studies and uses of thermions.

Since Michael Faraday's classic theories on electrolytes being composed of many discrete positive and negative charged particles, and following Johnstone Stoney's 1874 naming of these negative particles as "electrons", the charge on one electron was known, albeit not very accurately.

By 1897, J.J. Thomson, working at the Cavendish Laboratory in Cambridge, had extended the thermionic work making cathode ray tubes, the precursor of the cathode ray oscilloscope. They called the thermionic stream "cathode rays" and measured the mass of and the charge

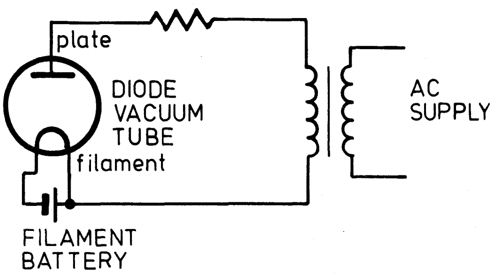
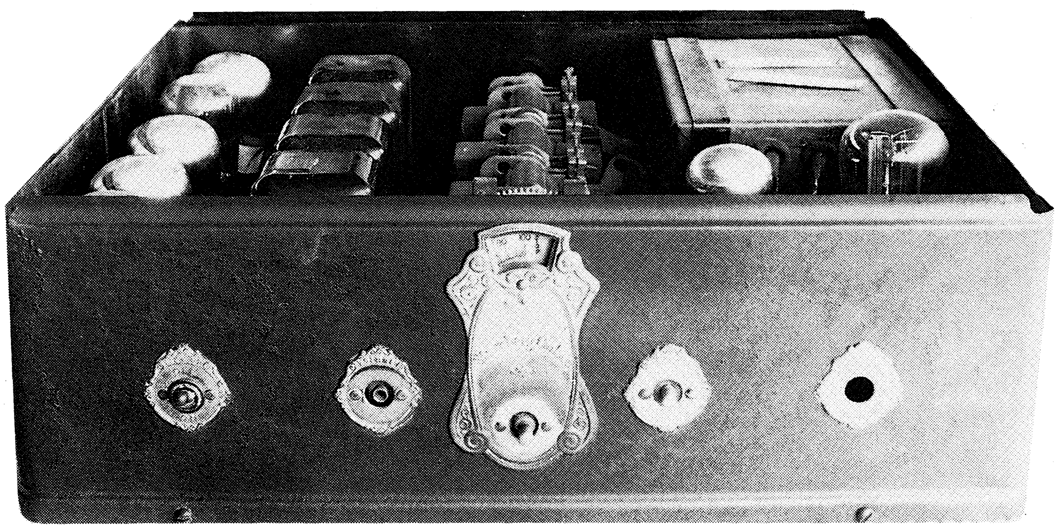



*Figure 1: AC rectifier diode.*



*Stromberg Carlson radio of the 1920s — seven valves, four gang tuning capacitor, mains-operated, rectifier type 280 on extreme right.*

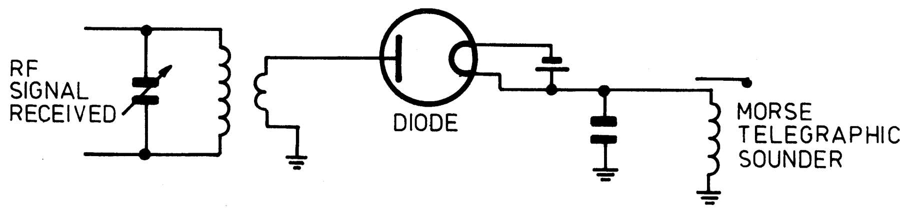



***Figure 2: RF detector diode for Morse telegraphy.***

carried by each thermion, finding the value of each charge to be the same as the charge on one charged ion in an electrolyte.

Thus the thermions and cathode ray particles were first identified as being electrons.

English scientist, Sir John Ambrose Fleming, continued work on the primordial electronic valve. The number of electrons escaping from the hot wire was found to increase approximately exponentially with its absolute temperature. At temperatures around 5000° roughly one electron in every 200 in the filament was escaping, which means a very large number of electrons. This stream is a real electric current, a fact known to the early researchers.

Fleming saw that, as the electrons would flow to the anode only when the anode was positive, if alternating current was applied to the anode, unidirectional current would flow on each positive half cycle, and nothing would happen on the negative half cycle. He had invented the fundamental rectifier circuit by 1904. (See Figure 1.)

Regarded as a sort of one-way valve, to borrow an hydraulic analogy, the name "valve" thereafter stuck to all electronic vacuum tubes. The Americans stuck to the title vacuum tube, or electron tube, but interestingly, in the USA today, the large high-power silicon thyristor groups (up to 800,000 volts and 10,000 amps) and the newly resurrected mercury-arc rectifiers are often called valves, technically quite correctly.

For power frequencies, around the turn of the century, there were rotary methods for the conversion of ac to dc, but Fleming took one giant leap forward and applied alternating current at radio frequencies to his one-way valve.

His great contributions to electronics began in 1904 when he built a vacuum tube diode having small enough capacitance to be able to rectify small radio frequency currents. Thus was born the first high-sensitivity RF signal detector, opening the way for longer distance radiotelegraph communications as in Figure 2. Rectified RF currents could now directly operate a telegraphic electromagnetic morse code sounder.

## The triode valve

Vast improvements in radio communications derived from the inventive mind of Lee de Forest, who in 1907 added to the vacuum tube diode a small wire grid between filament and anode. He found this acted as a control grid, with voltage varying the number of electrons flowing, hence varying the anode current as in Figure 3. By placing a high value resistor or inductance or transformer in the anode circuit the anode current causes a varying voltage drop across this component. Because this varying voltage across the anode circuit impedance is larger than the little voltage signal applied to the grid, voltage gain is achieved. Thus was born the triode amplifying tube, known at first as the "De Forest Audion" and following De Forest to broadcast a concert by Enrico Caruso from New York in 1910 using amplitude modulation. The amplification property was the essential link which made high power transmitters, long distance reception and sensitive radio and TV receivers possible, as well as enabling the early invention of voice, and music modulation methods.

The triode turned out to be a very linear amplifier tube, amplifying signals with little distortion effect. For this the triode remained in use for threequarters of a century. The name "triode" comes from this tube's use of three fundamental electrical elements: filament (or cathode), control grid and plate.

Application of this vacuum triode tube, called the "audion", to an RF oscillator circuit

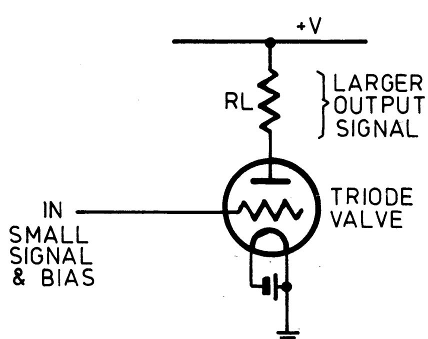



***Figure 3: basic triode amplifier tube.***

by De Forest and Edwin Armstrong in 1913 enabled radio transmitters of controllable frequency and bandwidth to replace the sledgehammer-like spark transmitters of early radio. By the next year vacuum tube triode amplifiers made possible undersea intercontinental telephone circuits.

Sadly, however, it was found that the gain of all vacuum triodes is less at high frequencies. Another failing of the vacuum triode RF amplifier was the way its low output (plate) resistance loads an RF tuned circuit. (See Figure 4(a).) Valve output resistance or plate resistance means how much the anode voltage drops as a consequence of a change in anode current, a fundamentally important property of every valve.

## Tetrode valves

Walter Schottky is a name known to all modern computer buffs (whose state-of-the-art computers use solid state 54/74LS series Schottky high speed TTL digital logic). In 1916 he gave us the tetrode vacuum tube, which has an extra grid element interposed between the control grid and anode. This results in operation quite different from that of a triode, (see Figure 4(b).) With its much higher plate resistance the tetrode (four electronic elements) does not load the following tuned circuit as much as a triode RF amplifier.

Because of this, the quality factor or "Q" of the tuned circuit can be much higher, vastly improving RF amplifier stages by narrowing their bandwidth, ie, raising the selectivity and giving sharper tuning. This advance allowed many more radio stations to be on the air without interference.

## That valve sound

Even today there are guitarists who prefer the "valve sound" in their high-powered stage amplifiers. This philosophy persists, particularly among bassists and 12-string artists, those using the two extremes of the frequency range.

If this preference has real foundation one place to look for a technical reason could be the elusive TIMD, transient intermodulation distortion, which is certainly more prevalent in solid state audio amplifiers than in valve amplifiers. Not that there is any good reason why this should be the case – it's just a habit some slack solid-state designers have allowed to creep in.

Let us now look into just why valves work. A few valves still survive in today's fast and miniature world. The survivors are specialised valves: very big ones for large radio transmitters and strange looking ones for extremely high frequency work, and of course CRO tubes, TV picture and camera tubes. There are also a few little valves in positions where a low-level signal of a couple of microvolts must be amplified by an amplifier having extremely high input impedance in the gigohm region. Such a situation occurs in areas like neuro-pharmacological or neurobiological research establishments.

## How it works

The innards of a valve is mostly nothing; most of the volume of the vacuum tube is just that. It uses the properties of a free-moving electron stream generated by electron emission from a hot surface, as in Figure 5.

Such electrons are attracted and accelerated by a positive anode some-

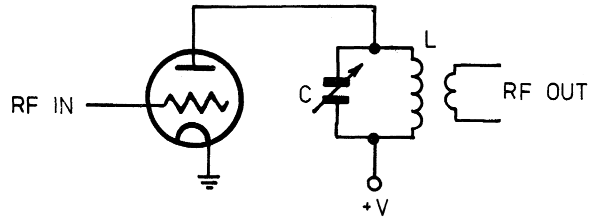



***Figure 4(a): a triode RF amplifier, because of the low value of plate output resistance, loads the following tuned circuit, L,C. This reduces the Q of the tuned circuit, spoiling the tuning characteristics.***

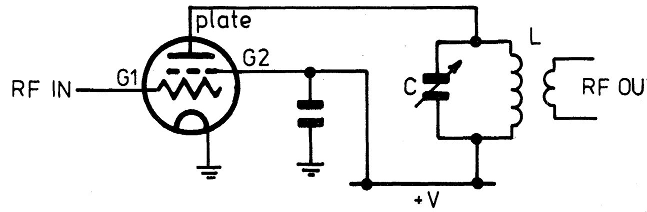



***Figure 4(b): tetrode valves, with screen grid G2, have higher output resistance at the plate, giving less loading of the tuned circuit, L,C. Thus, tuned circuit Q is higher, giving sharper tuning.***

where, and along the way the stream of electrons is controlled in number by being made to pass through a sparse grid carrying control potential.

Figure 5 shows the fundamental operation of all amplifying vacuum tubes. The hot surface at the left is called the "cathode", symbol K, because it is the more negative end of the electron stream. The cathode cylinder (in most vacuum tubes) is heated by a filament inside.

The cathode surface is coated with materials such as caesium and thorium oxides. The hot cathode emits copious quantities of electrons which gather in a cloud around the cathode.

When a high positive potential applied to the anode causes a strong electric field between anode and cathode, this field accelerates some of these negative electrons towards the anode. But when travelling between cathode and anode within the evacuated tube such current does not obey Ohm's law.

On the way the electrons in the stream go through the very open mesh grid of wires called the "control grid", G1. If this grid has no potential, the electrons just shoot straight through it on their way to the anode.

## Control grid

If we apply a small negative potential to the grid it interferes with the large anode-cathode electric field and reduces the number of electrons in the stream. Thus the anode circuit current is reduced as in Figure 6.

A +250 volt supply is connected via a load resistor RL, to the anode. The electron stream from grounded cathode to positive anode within the valve continues outside the tube as an ordinary electric current in the wires and the resistor RL, up to the positive supply rail at +250 volts potential.

Outside the valve this current does obey Ohm's law, causing a voltage drop across RL proportional to current. Electrons, being negative, are flowing up from cathode K through the valve, via the anode and the resistor RL to the +250 volt rail. We still speak in the conventional terminology saying that "conventional" current is flowing in the other direction, ie, from the +250 volt rail, down through RL and the tube to the grounded cathode.

The more positive the grid the larger is plate current, producing a larger voltage drop across RL, ie, plate voltage reduces. Therefore we say the valve produces signal inversions.

The controlled electron stream within the vacuum tube becomes a controlled electric current passing through load resistor RL. This produces a controlled voltage drop across load resistor RL which can be much greater than the controlling potential applied to valve control grid G1. The ratio of change in the control grid potential to the resultant change in voltage drop across RL is the significant (inverted) voltage gain of this valve and circuit.

Thus the valve and associated circuit can be a voltage amplifier having considerable voltage gain.

***Part of Stromberg Carlson's 7-valve radio. RF section on the left, tuned coils in centre, 4 gang tuning capacitor on the right. Mains-operated, valves are 4 pin or 5 pin.***

## Cold cathode tubes

Electrons can also be made to leave the cold cathode surface of suitable materials in vacuum by bombarding such cathodes with light of suitable wavelength. This is the photoelectric effect in which the emitted charge carriers were first identified as being electrons by Lenard in 1899.

The frequency and wavelength of the incident light, as in Figure 7, must be such that the energy of each photon of light is greater than the energy an electron of the cathode surface material must acquire before it can escape (work function).

The energy of each photon is proportional to the frequency (colour) of the light, not its brightness, as Einstein declared in 1905.

## Cold cathode rectifiers

Electrons can be made to leave a solid cathode by other methods, for example, the attraction of a strong positive electric field, or cathode heating by energetic gas ion bombardment.

Commercial examples once used included the RCA gas-filled cold cathode rectifier tube. This tube, Figure 8, required a minimum voltage of 300 volts peak to begin ionisation of the gas. Then the energy of gas ions heated the cathode causing it to emit electrons which travelled to whichever anode was positive (but not to the other negative anode). Thus rectification of high voltage ac was performed.

## Common vacuum tubes

In vacuum tube days thermionic emission of electrons from a hot filament or an indirectly heated cathode was by far the most commonly used method of producing the electron stream in evacuated tubes. Thousands of vacuum tube types were manufactured and used.

The simplest tube in common use in 240 volt ac powered equipment was the hot-filament-cathode full wave vacuum rectifier tube type 80 (at first called type 280) with its 4-pin base, or the equivalent type 5Y3G (octal base), and the 5Y3GT.

Original American naming for vacuum tubes was an almost random numbering system: other rectifiers included types 83, 83-V and 84, but the trouble was that the numbering system told the user nothing about the tube.

For example tubes types 40, 41, 42 and 45 were all utterly different, ranging from a small battery operated triode with 5-volt filament (type 40) through the power output pentode with 6.3-volt heater (type 42) to the larger power triode with 2.5-volt heater (type 45).

## Valve numbering system

After a while the Americans got sick of such confusion and invented a new numbering system. An example is the full wave rectifier type 5Y3GT, in which the first figure "5" denotes that the filament requires 5.0 volt supply; "Y" is an identification; "3" says that the tube contains three electrical elements (one filament and two anodes in this case); "G" indicates a glass envelope and lastly the addendum "T" means a "bantam" or small glass envelope.

Furthermore, most tubes carrying "G" or "GT" endings were octal (8-pin with central keyed tongue) base types. The octal base was an attempt to rationalise the sockets used, as the old type-numbered valves might have four, five, six, seven or eight pins as required, hence the socket manufacturers had to make five different types of sockets.

Vacuum tubes having metal envelopes (rather than glass) were popular in the USA but were seldom seen here until the war disposals market gave us millions of types 6SR7, 6H6, 6SJ7, 6J7, etc. The metal envelopes could be grounded, making an excellent electrostatic field.

Two of the above tubes include an "S" before the identifying letter, which signified a "single-ended" tube, meaning that the grid connection was via a base pin, rather than a top grid-cap. Thus tube type 6SR7 was a development from the pre-war 6R7 (metal), 6R7G (glass) and 6R7GT (small glass envelope).

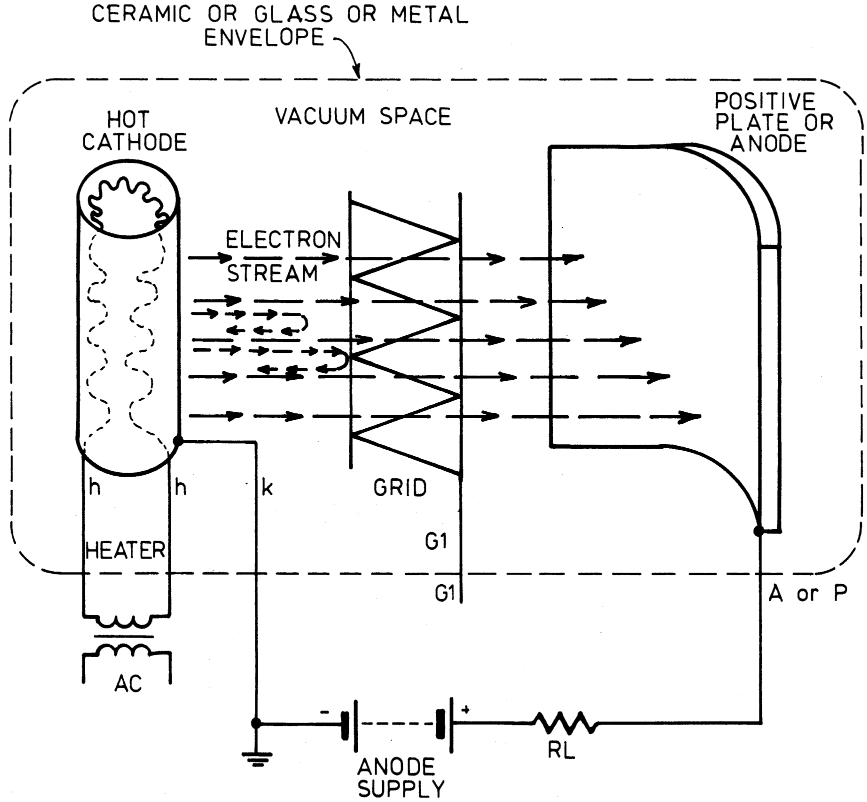



***Figure 5: fundamental triode vacuum tube, electron stream and control grid. Grid potential controls the number of electrons arriving at the plate.***

The single-ended idea arose during World War 2, doubtless because the flying lead to the top grip cap of the pre-war double-ended types was vulnerable to damage. To be complete we had better say that the 6SR7 contained seven elements (as the final character in its type name denotes), being heater, cathode, control grid, anode and two small diode anodes for diode AM demodulation and AVC rectification. The metal envelope shield counts as the seventh element.

## Power supply circuit

A commonly used circuit for the type 80 or 5Y3GT full wave rectifier tube is shown here as Figure 9. But first, lest modern electronics bods (so used to low voltage solid state technology) be caught by the high voltages inherent in valve equipment, let me repeat that all mains operated valve equipment uses dangerous, lethal voltages.

The mains transformer has a 700 or 770 volt secondary winding centre tapped. The centre tap becomes the negative output, so is grounded. Each side of the secondary feeds one rectifier plate while the isolated 5 volt ac secondary winding supplies the 5Y3G filament which (acting as cathode) becomes the positive output.

Each rectifier plate (anode) conducts when positive by attracting electrons emitted by the hot filament. The tube has a large voltage drop between anode and filament, and also the inductance L has considerable resistance. So a 700 to 770 volt transformer secondary produces a smoothed DC output from the filter of about 250 volts, depending on load current. Incidently those transformers were known as 350-CT-350 or 385-CT-385 power transformers – the figures 700 or 770 volts were never expressed. Another common size was 285-CT-285 volts.

For higher voltages and currents the rectifier types 5Z3, GZ34/5AR4, 83V, 5V4 or 5U4GB were also used.

As more new valve types were developed manufacturers soon used up the alphabet

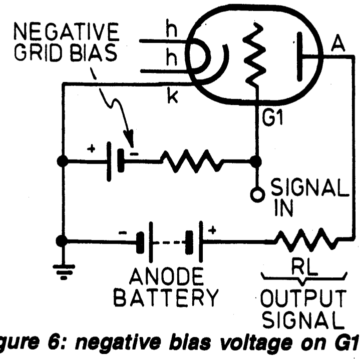



***Figure 6: negative bias voltage on G1 reduces number of electrons in stream, so reducing the anode current and hence output voltage.***

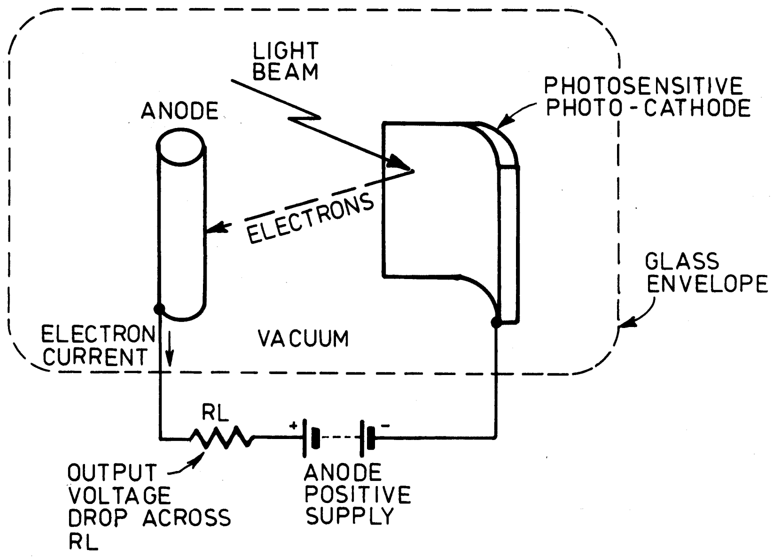



***Figure 7: cold cathode photo tube. Light falling on photo-sensitive photocathode causes electrons to be emitted. These electrons are attracted to the anode, forming an electric current which produces output signal proportional to light intensity.***

so for further new types two distinguishing letters had to be used. An example is the 5AR4 full wave vacuum rectifier tube which has a cathode sleeve over the 5 volt heating filaments to obviate the reduction of heating filament metal by electron and ion loss.

## *European valves*

The Europeans, mostly Philips and Mullard, always had their own valve type-numbering systems, consisting of a letter denoting heater voltage, followed by one, two or three letters describing the tube type and function. Then follows a two figure distinguishing number. Examples were type DL96 where "D" told us that the filament voltage was 1.4 or 2.8 volts, "L" said that this tube was an output power pentode, and the "96" was its distinguishing number.

Another tube was the ECC84, "E" for 6.3 volts heater, "C" for double triode structure and "84" to distinguish it from all the other ECC-types. An "F" denoted pentode, "CF" a triode-pentode double tube etc.

They had a neat way of denoting a premium quality long life tube by swapping the order of characters in the name. Thus type ECC83 denoted an ordinary quality double triode while E88CC was a special quality long life construction.

## *New tube constructions*

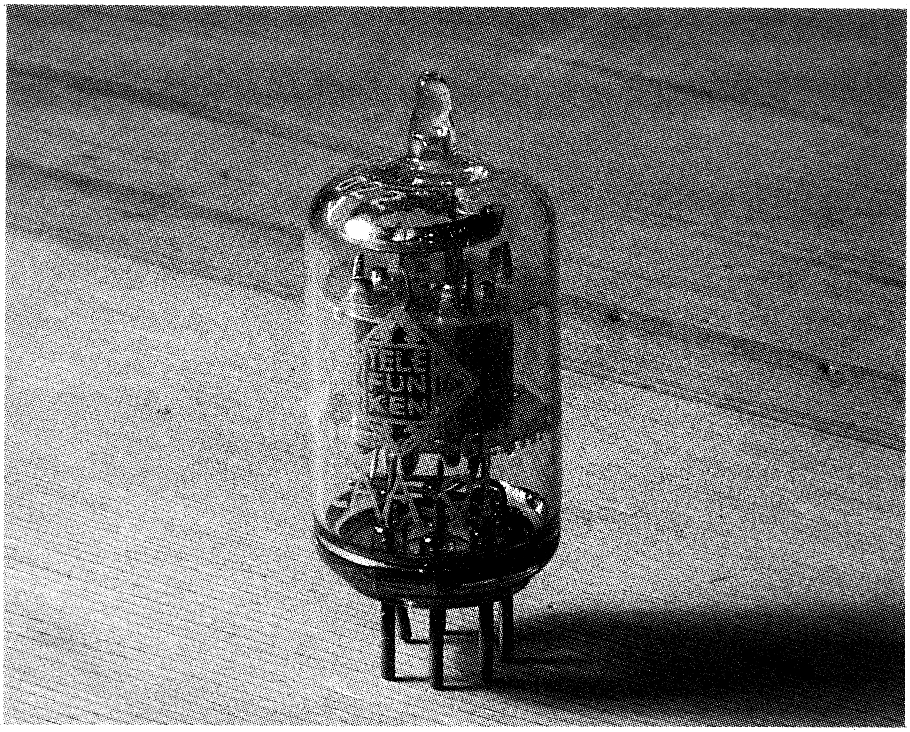
Late in the valve era we saw the introduction by most manufacturers worldwide of "baseless" tubes without any bakelite base, the pins just protruding through the glass tube bottom. There were 9-pin and 7-pin types in this very popular series, known in Europe as "noval" or in America as "miniature" tube types.

Many of the American efforts in this construction had type numbers beginning with "6C", such as the highly successful small video power pentode type 6CL6. A full lineup of noval/miniature tubes filled most positions in the last valve-operated radio and TV receivers sold in Australia.

The rectifier tubes of this construction were often the "EZ" types (Z for full wave rectifier). One of these types became infamous for its habit of metal-plating the inside of the glass base by a vacuum metal-sputtering-deposition (which of course wasn't supposed to happen). The result was metal plating

COLOUR, FREQUENCY AND WAVELENGTH OF LIGHT

| Colour | Frequency | Wavelength |
|---|---|---|
| Far ultraviolet | 3,000,000 GHz | 100 nm |
| Near ultraviolet | 750,000 GHz | 400 nm |
| Violet | 714,000 GHz | 420 nm |
| Blue | 652,000 GHz | 460 nm |
| Green | 536,000 GHz | 560 nm |
| Yellow | 509,000 GHz | 589 nm |
| Orange | 476,000 GHz | 630 nm |
| Red | 413,000 GHz | 725 nm |
| Near infrared | 300,000 GHz | 1.0 micron |
| Mid infrared | 3000 GHz | 100 microns |
| Far infrared | 300 GHz | 1.0 mm |




***The cold cathode rectifier type OZ4G.***

electrolytic capacitor to prevent loss of stage gain, otherwise signal voltage developed in this cathode resistor is in fact negative feedback.

But in some high-class negative feedback audio amplifiers, such as one version of the famous Williamson amplifier, the cathode resistors were left un-bypassed to avoid the low frequency phase shifts which bypass capacitors introduce. The resultant small loss of gain was made up by more stages.

While the grid remains at ground potential, a positive (to ground) potential applied (by voltage drop in RK) to the cathode is equivalent electrically to a negative bias on the grid (as seen by the cathode).

Many circuit-design techniques used in today's solid-state equipment are simply following the ideas developed by valve engineers. For instance modern amplifiers using a solid state JFET transistor make use of a bypassed source resistor to apply negative bias to the gate of the JFET. **eti**

around all pins inside the tube, bridging them all together, shorting out the whole power transformer secondary winding, resulting in a burnt-out power transformer and sometimes a fire. Quickly an improved tube appeared on the market, but not before many radio servicemen replaced a multitude of power transformers and rectifier tubes.

## Voltage amplifiers

Using the Philips style "EF" series, or the American tubes like the famous 6J7G, thousands of high gain audio amplifier stages were built across the world by hi-fi enthusiasts. These types were all pentodes, ie, five element tubes, containing 6.3-volt heater, cathode, control grid G1, screen grid G2, suppressor grid G3 and anode. The heater was not counted in the number of tube elements as it played only a thermal (non-electronic) role.

Small audio signals input at A in Figure 10 were capacity coupled to the control grid G1, from which a grid leak resistor RG1, usually 0.5 megohm, held the grid at dc ground potential. As the grid took almost no input current, RG1 has negligible voltage drop across it. The anode was connected to the +250-volt rail through load resistor RL, which was quite highly valued, often 56,000 ohms.

Plate current was usually about 2.0 milliamps under control of the negative grid-cathode bias applied. This bias voltage was often derived, as Fig 10 shows, by causing a DC voltage drop across a resistor RK in the cathode to ground return path. This resistor RK developed a DC voltage drop, typically 2.5 volts, positive at the cathode terminal.

Often this resistor was bypassed using an

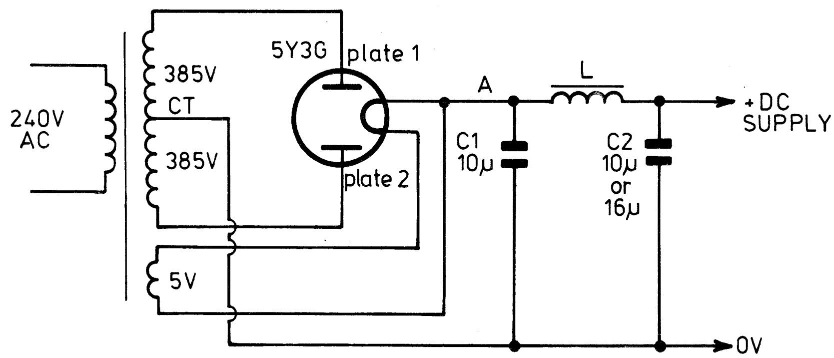



***Figure 9: a standard circuit for dc supply using 385-CT-385 transformer and capacitor input filter. In earlier years the 385/385 transformer was popular as the loudspeaker field coil (which has considerable resistance) was used as the filter choke.***

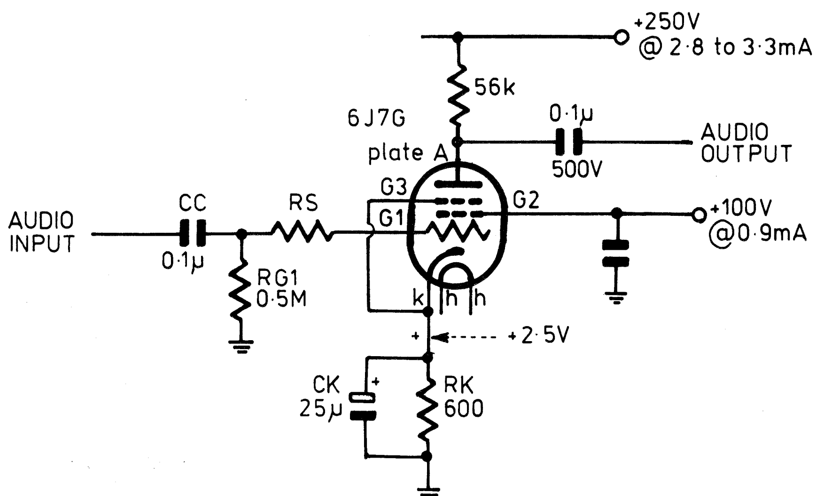



***Figure 10: pentode audio voltage amplifier using the common old 6J7G tube. Fit grounded valve shield around tube. G1 is a top cap. RS is a parasitic stopper carbon resistor.***