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This page is dedicated to explaining the fundamentals of electron tube technology.

Electron Tubes are electro-mechanical devices that use electrons to perform work.

1. ELECTRONS

Note: The following text may be heresy to modern scientists, however this was the state of the art in 1959.

The RCA Receiving Tube Manual RC-19 (1959) describes "electrons" in this way:

"All matter exists in the solid, liquid, or gaseous state.

These three forms consist entirely of minute divisions known as molecules, which, in turn, are composed of atoms.

Atoms have a nucleus which is a positive charge of electricity, around which revolve tiny charges of negative electricity known as electrons.

Scientists have estimated that electrons weigh only 1/30-billion, billion, billion, billionth of an ounce, and that they may travel at speeds of thousands of miles per second.

Electron movements may be accelerated by the addition of energy.

Heat is one form of energy, which can be conveniently used to speed up the electron. For example, if the temperature of a metal is gradually raised, the electrons in the metal gain velocity. When the metal becomes hot enough, some electrons may acquire sufficient speed to break away from the surface of the metal. This action, which is accelerated when the metal is heated in a vacuum, is utilised in most electron tubes to produce the necessary electron supply."

2. PUTTING ELECTRONS TO WORK IN ELECTRON TUBES.

The RCA Receiving Tube Manual RC-19 (1959) and the RCA Transmitting Tube Manual TT-4 (1956) propose that:

"Electrons are of no value in an electron tube unless they can be put to work.

Therefore, a tube is designed with the parts necessary to utilise electrons, as well as those required to produce them.

Now, the transfer of electrical energy through a circuit involves control of two factors - rate and direction.

The rate of energy transfer is determined by the number of individual electron charges moving unidirectionally through the circuit in a given interval of time and is proportional to the applied voltage.

The direction in which the electron charges move is determined by the polarity of the applied voltage.

In electrical circuits, control of the direction of current flow is necessary when the power source produces ac (alternating current) voltages and currents and the load requires a uni-directional current."
Devices that are used primarily to control the direction of current flow are known as "rectifiers".

All such devices (rectifiers) however are also rate control or rate limiting devices in the sense that they have a finite current carrying capacity.

Now, electric charges may be transferred through a circuit by several methods.

In one method, kinetic energy is transferred between adjacent electrons within the molecular structure of a conductor. This method is employed in switches, rheostats, potentiometers and other devices that utilise conductive materials as control electrodes.

Because the currents through such devices are controlled by mechanical means, the speed with which the amount or direction of current can be changed is limited by friction or inertia.

In a second method, individual electrons are transferred in one direction through semi-conducting materials such as in silicon diodes and transistors. This method has the advantage that the rate of current flow may be controlled by electric fields.

In a third method, individual electrons are transferred through a low-density, non-conductive medium, such as a vacuum or low pressure gas. This method is used in electron tubes and has the advantage that both rate and direction of current flow may be controlled by electric fields.

Because these fields, as well as the electrons, have negligible inertia, electron tubes can effect changes in the value and direction of electric current at speeds considerably higher than those obtainable with mechanically operated devices.

3. ELECTRON TUBES

3.1 CONCEPT - VACUUM TUBES, ELECTRON TUBES, THERMIONIC VALVES

The ELECTRON TUBE is an electro-mechanical device that enables an electrical current to be controlled be external electrical means.

The Vacuum Tube is commonly known around the world by the names "Vacuum Tube, Electron Tube, Radio Tube or Thermionic Valve."

The RCA Receiving Tube Manual RC-19 (1959) describes it so:

"The Electron Tube is a marvellous device. It makes possible the performing of operations, amazing in conception, with a precision and a certainty that are astounding. It is an exceedingly sensitive and accurate instrument - the product of co-ordinated efforts of engineers and craftsmen. Its construction requires materials from every corner of the earth. Its use is world-wide. Its future possibilities, even in the light of present day accomplishments, are but dimly forseen; for each development opens new fields of design and application. The importance of the Electron Tube lies in its ability to control almost instantly the flight of the millions of electrons supplied by the cathode. It accomplishes this control with a minimum of energy. Because it is almost instantaneous in its action, the electron tube can operate efficiently and accurately at electrical frequencies much higher tha those attainable with rotating machines. An Electron Tube consists of a cathode, which supplies electrons, and one or more additional electrodes, which control and collect these electrons, mounted in an evacuated envelope. The envelope may be made of glass, metal, ceramic, or a combination of these materials."
3.2 DESIGN

In its simplest form, an electron tube consists of a cathode (the negative electrode) and an anode or plate (the positive electrode) in an evacuated sealed envelope.

The envelope may be made from glass, metal, ceramic, or a combination of these materials.

More complex types may also contain one or more additional electrodes which control and collect electrons. The electrodes are encased in the evacuated envelope and have the necessary connections brought out through air-tight seals.

The air is completely removed from the envelope to allow free movement of the electrons, and to prevent injury to the emitting surface of the cathode.

The purpose of the cathode is to furnish a continuous supply of free electrons; the plate collects these free electrons.

Now, rate control requirements in electrical circuits range from an occasional on-off switching to continuous variations occurring several billion times per second.

The rate at which electrons are collected by the plate (the plate current) is determined by the the number of free electrons available and by the polarity and the strength of the electric field between the plate and cathode.

Tubes that provide this form of control are known generically as "amplifiers".

Power tube amplifiers are capable of controlling relatively large amounts of energy.

(Note: All triode and multi-grid power tubes are inherently rectifiers as well as amplifiers, because they deliver unidirectional current regardless of the kind of energy provided by the power source.)

Power tubes and rectifiers are usually operated so that the number of electrons available is constant. Consequently, the rate of collection or current flow is determined by the characteristics of the internal electric field.

WARNING - VACUUM TUBES OPERATE AT HIGH VOLTAGES THAT CAN BE FATAL OR CAUSE PERMANENT PHYSICAL MALFUNCTION OR DISABLEMENT.

DO NOT ATTEMPT TO CONSTRUCT OR WORK ON AN AUDIO AMPLIFIER UNLESS YOU HAVE BEEN TRAINED OR ARE OTHERWISE QUALIFIED TO DO SO - WE WANT YOU TO LIVE TO ENJOY THE FRUITS OF YOUR LABOUR.

3.3 OPERATION

When the cathode is heated, electrons leave the cathode surface and form an invisible cloud in the space around it.

Any positive electric potential within the evacuated envelope offers a strong attraction to the electrons (unlike electric charges attract; like charges repel).

Such a positive electric potential can be supplied by an anode (plate) (positive electrode) located within the tube in proximity to the cathode."

The Vacuum tube is called a "Valve" is some countries because it performs the traditional function of the valve - ie a valve controls or regulates the flow of fluid in a device, usually a pipe or tube, by limiting the volume of flow of fluid to a pre-determined proportion, or percentage, of the maximum possible rate.

A "valve" is also a "regulator". The function of a "regulator" is to limit the rate, pressure or volume of flow to within a range controlled within pre-determined limits.

The current flowing through a vacuum tube is regulated by the external circuitry - to control the current flow between pre-determined limits.

As we will see in this paper, electrical current behaves just like a fluid and this analogy will be referred to several times.
4. HOW VACUUM TUBES WORK

4.1 BASIC CONCEPT

The Vacuum Tube is an extremely simple device.

In its simplest form, the "diode", the vacuum tube comprises a cathode and an anode mounted in a vacuum chamber.

A high direct current voltage is applied between the anode and cathode. The cathode is heated to stimulate it to emit electrons. The electrons are then free in space in the vacuum tube, and are attracted to the anode, setting up a stream of electrons, just like water in a pipe.

In a diode the volume of electrons flowing is controlled by the load in the circuit. Diodes are therefore not "valves".

The maximum current that can flow in the circuit ("prospective current") is determined by the capacity of the mains, battery or generator supply limited by the sum of the internal impedances (reactance) of the vacuum tube, circuit components (eg transformers) and the load.

Diodes have limited application and are therefore mainly used to rectify (convert) alternating current to direct current, in which application they offer outstanding performance and reliability if used correctly.

Vacuum tubes are not very efficient, giving up about half the input energy as heat, transferred to the atmosphere and mounting components by convection and conduction respectively. Electrons generated by the hot cathode but not used by the load are also released as heat, described as "plate dissipation".

In directly heated tubes the cathode is heated by itself and is called a "filament" because the electrons are emitted directly from it, just as in a light bulb. Filament warm-up time is quick so current flows soon after the tube is switched on.

In indirectly heated tubes - ie where the cathode is physically separate to the heater, the cathode is called a "cathode", to describe its true function. Cathode warm-up time is slow, so current flows some time after switch on - usually controlled by tube design to about 11 seconds from cold to full warm up.

For a comprehensive explanation of how tubes work see 1952 Text US Army TM11-662 and Airforce Text TO16-1-255

4.2 ELECTRON TUBE TYPES

Electron Tubes are designated by the number of electrodes used in their design and construction.

In directly heated tubes the "filament" is classed and counted as an electrode.
In indirectly heated tubes, the "heater" is not classed or counted as an electrode.
In most cases except the "monode" the Electron Tube contains an ANODE ( the "plate") and a CATHODE (the directly heated "filament" or indirectly heated "cathode"). The remaining electrodes are called "grids" and are used to control the flow of electrons between cathode and plate.
Certain types of gas filled tubes may vary slightly from the above configuration.

a) MONODE - Single Filament Electrode eg LIGHT GLOBE or LAMP. (Not usually classed as an "Electron Tube" even though they are typically a vacuum tube.)

b) DIODE - Two electrodes
c) TRIODE - Three electrodes
d) TETRODE - Four electrodes
e) PENTODE - Five electrodes
f) HEXODE - Six Electrodes
g) HEPTODE - Seven electrodes
h) OCTODE - Eight electrodes
i) BEAM POWER TUBE - Further refinements produced the Beam Power Tube, which may be a tetrode or pentode
whose performance is enhanced by mechanical manipulation of the electron beam, to produce substantially greater efficiency, power output and reduced distortion.

Examples of the Beam Power Tube are demonstrated in the 6L6 family of designs, which include the 6L6GT, 807, 1614, 1625, 5881, 7027A, 7581A/6L6GC and KT66.

Other Beam Power Tubes include 6AQ5, 6CZ5, 6DZ7 (2 x 6BQ5), 6V6GT, 6005, 6550/KT88, 6973, 7581A/KT66, 8417, KT66 and KT88.

These tubes evolved from the 42 and 6F6 family which were pentodes. Comparison of their performance shows reduced heater power requirements and substantially improved performance.

Please note the 6BQ5/6DZ7/EL84/7189, 6CA7/EL34, and 7591/7868/6GM5 families are not Beam Power Tubes but are Pentodes.

Beam Power Tubes may generally be identified by a box-like structure on top of the plate assembly, which extends down inside the tube between the plate and the control grids to direct electron flow.

For an overview of Beam Power Tube design and application see RCA Beam Power Tubes

4.3 TUBE FUNCTION

Electron Tubes may be used in a very wide range of applications.

In audio amplifier and modulator applications the primary functions of Electron Tubes are:

a) Rectifier  
b) Voltage Stabiliser or Regulator  
c) Voltage Amplifier  
d) Phase Splitter or Phase Invertor (push-pull circuits only)  
e) Power Output

Tube signal output is controlled by the concurrent application of direct current (DC) and alternating current (AC) voltages to the electrodes of the tube.

Most electron tubes are provided with pins to enable insertion into or removal from a socket, to which external control circuit wiring is attached, however some more modern types have wires instead of pins, to enable direct wiring into apparatus.

Despite the socket/pin system suggesting unreliability, electron tubes can provide reliable service for many, many years - depending upon a range of factors including circuit design.

It is common for electron tubes that have been in storage for 60 years to reliably operate first time when energised.

The electron tube is truly one of the most important devices to benefit mankind ever invented.
1. TRIODE OPERATION OF POWER TUBES

1.1 TRIODE TONAL CHARACTERISTICS

It is well established that many listeners prefer the "soft" and certainly pleasant tonal characteristics of triodes.
However triodes suitable for audio power operation are becoming extremely scarce in the world market and aftermarket prices for popular types have increased astronomically in recent years.

So it is often more convenient to use tetrodes, pentodes or beam power tubes because of availability, cost or convenience.

An often overlooked design feature is that most popular audio power triodes have directly heated filaments, thus creating a potential for problems in dealing with hum, reliability and power supply - whereas most popular tetrodes, pentodes and beam power tubes incorporate indirectly heated cathodes - ie use separate heaters.

Most tetrodes, pentodes and beam power tubes can be successfully operated as triodes in either voltage amplifier or power tube applications, by connecting Grid #2 directly to the Plate.

In the case of triode operation of pentodes and beam power tubes, Grid #3 or the electron beam shield respectively, are still usually connected to the cathode or filament, as is the case for normal tetrode or pentode connection.

The characteristics of a pentode/beam tetrode as a triode are largely determined by the Grid#1/Grid#2 amplification factor which is dependant not on the Anode/Cathode spacing but the Grid#1/Cathode and Grid#2/Cathode spacings.

The function of the Plate in a triode connected multi-grid tube is merely to collect all the electrons that have been attracted by the Screen-Grid acting as an ANODE which, because of its open structure, will collect relatively few electrons - which probably accounts for the increased allowable screen voltage when so connected.

My personal view is that to ensure tube operation - including Cathode Current, Plate Dissipation and Screen-Grid Dissipation - is maintained within design limits, the applied DC Plate and Screen voltages should never be greater than the rated Screen-Grid Voltage.

1.2  SUITABLE TUBES

The Radiotron Designers Handbook 4th Edition 1953 says:

(i) Triode operation of pentodes

Any pentode may be operated as a triode, provided that none of the maximum ratings is exceeded, and the characteristics may readily be calculated if not otherwise available.

When the cathode current of a valve is shared by two collecting electrodes (e.g. plate and screen) the mutual conductance of the whole cathode stream (i.e. the “triode $g_m$”) is shared in the same proportion as is the current.

Let $I_c = \text{cathode current}$

$I_{cs} = \text{screen current}$

$I_b = \text{plate current}$

$g_m = \text{pentode transconductance (to the plate)}$

$g_t = \text{triode transconductance (with screen and plate tied together)}$

and $g_s = \text{screen transconductance (with pentode operation)}$.

Then

$I_c = I_{cs} + I_b$  \hspace{1cm} (1)

$g_t = g_m + g_s \text{ (by definition)}$  \hspace{1cm} (2)

and $g_m/g_s = I_b/I_c$  \hspace{1cm} (3)

If it is desired to find the screen transconductance, this can be derived from the expression

$g_s/g_m = I_c/I_b$ \hspace{1cm} (4)$

or $g_s/g_t = I_{cs}/I_c$ \hspace{1cm} (5)$

Manufacturer's data is available for triode operation of some popular types of tetrode, pentode and beam power tubes such as EL34/6CA7, 6V6GT, KT66, KT88, 807, 6146. However, typically they are pragmatically assigned a significantly higher Grid #2 rating than for either tetrode or pentode connection.

The higher triode connected manufacturer's rating should only be used with great caution as it increases the risk of
Where tetrodes and pentodes are connected as triodes care must be taken to ensure the Plate and Screen Voltages are not too low, to prevent the Screen-Grid from becoming the primary anode and thus attracting too many electrons, thus exceeding Screen Dissipation rating and fusing the Screen-Grid.

For efficient and reliable operation, a minimum Plate and Screen B+ Voltage of at least half the rated Plate Voltage is therefore recommended. This obviously limits the choice of tubes to those tubes having an adequately high Screen-Grid Voltage rating.

In my opinion, the most likely candidates for triode connection are the:

- **6AQ5** (275 VDC) 7 pin
- **6V6GT** (275 VDC) Octal
- **6CZ5/6973** (285 VDC) 9 pin
- **5881/6L6GC/7027A** (400 VDC) Octal
- **KT88** (550 VDC) Octal
- **813** (1100 VDC) Giant 7 pin

All are well proven fine quality beam power tubes, each famous in its own right.

However with more careful selection and operating conditions, there are many other fine tetrodes and pentodes that are capable of excellent triode operation - such as the **EL34/6CA7 (425 VDC)** (Octal) and **EL84/6BQ5 (300 VDC)** (9 pin) pentodes.

### 1.3 OTHER OPTIONS

**STC BRIMAR**, in their *Valve and Teletube Manual #8 (1959)* state:

"Where Pentodes are connected as Triodes, the Suppressor Grid should be connected to the Cathode, unless otherwise stated" (end quote)

However as far back as 1940, RCA state that the Suppressor Grid (Grid #3) in Pentodes may be connected to the Screen Grid (Grid #2) to operate Pentodes as Tetrodes. It follows that in Triode operation of Pentodes, Grids #2 and #3 can be strapped to the Plate if preferred.

Unfortunately, it will be noted that many of the popular Pentodes, such as the 6BM8, 6BQ5/EL84, 6GW8 and 6M5, have their Grid #3 internally connected to the Cathode, leaving the designer only Grid #2 available to connect to the Plate for triode operation.

It may well be however that in those Pentode tubes (other than Beam Power Tubes described as "Pentodes" in British and European catalogues) having a separate pin connection for Grid #3 - eg EL34/6CA7, 803 and 837 - some benefit might be achieved by connecting Grid #3 to both Grid #2 and the Plate to form a composite equi-potential tube element for triode operation.

This option would certainly ensure a smooth flow of electrons through and beyond the Screen-Grid. Any electrons reflected from the Plate (Secondary Emission) should get caught up in the main electron stream and not present a problem.

No data sheets are available for this class of operation so some degree of experimentation would be essential.

I have no direct applications experience or information to verify this option.

### 1.4 Triode Operation - Audio Signal Output:

Of fundamental importance in audio amplifier design, is that when tetrodes, pentodes and beam power tubes are configured in triode connection, the Screen Grid SIGNAL voltage will ALWAYS appear in the Plate circuit because the Screen Grid is connected directly to the Plate - ie the electrons collected and diverted by the Screen Grids will appear in the output of the amplifier under all conditions between zero signal and full signal input.

Thus any distortion and/or effects upon frequency response and linearity of the AC signal in the Screen Grid circuit of triode connected tetrodes and pentodes will appear in the output of the amplifier.

This phenomenon also happens in ultra-linear connection - but only under linear controlled conditions determined by the output transformer primary turns and impedance ratios - that are quite different to Screen Grid behaviour under triode connection.

However this phenomenon does not happen with conventional tetrode and pentode configurations because the Screen Grid signal is bypassed to ground and does not appear in the output signal at all - even with negative feedback from the loudspeaker. Consequently tube behaviour and amplifier performance are very different when a particular tube type is configured in each of tetrode/pentode, ultra-linear or triode connections.

However, one major bonus from triode operation is that the changes in relative portions of Plate Current and Screen-Grid Current -
ie signal output power - that occur with changes in Grid #1 Voltage - as illustrated in Fig. 2 above - will not have material effect on the output signal because the Plate and Screen Currents are mixed together.

In other words, triode operation will provide a more linear output stage than tetrode or pentode configurations.

NOTE: Triode operation of tetrodes, pentodes and beam power tubes produces substantially less power output than when used in their design configuration - ie for any given Plate voltage, the power output from a triode will be substantially less than that for a tetrode, pentode or beam power tube.

It should also be noted that Grid #1 bias voltage will be proportionately higher for triode connection, hence driving voltage will be also proportionately higher. For most applications this increase could be substantial, necessitating a more complex driving stage arrangement than would otherwise be the case.

The tube manufacturer's data sheets should be consulted before proceeding with an amplifier design commitment.

1.5 Triode Operation - Grid Stopper Resistor:

It is important to retain the grid stopper resistor between Plate and Screen Grid, to prevent parasitic-oscillation in the tube. The grid stopper resistor must be mounted as closely to the tube socket pin as practicable to minimise RF signal pickup and minimise inductance in the wiring.

The usually recommended value is around 100 to 500 ohms (although many commercial amps connect directly, with no Grid stopper at all) however an empirical approach derived from the manufacturers' data described on my ultra-linear operation page suggests a value of around at least one half the Plate to Plate load impedance presented by the output transformer.

A value (per-tube) of half the Plate to Plate load impedance might be a good starting point to give the electrons sufficient incentive to travel the further journey to the Plates instead of taking the easy path home. More resistance may be required though to achieve the desired effect - after all, electrons are lazy critters and always take the easiest route they can, even if it means increasing density - ie crowding into a small area of a conductor or electron beam. For those mechanically minded, electron flow behaves like a fluid.

Even if the Grid Stopper resistor has a value equal to the Plate load impedance, the current flow in Grid #2 will still be significant.

Unfortunately, the tube handbooks tell us that the Screen to ground return path must be of low AC low impedance. One way out of this is to shunt the Grid-stopper with a suitable value of capacitor so that the Screen is grounded via the Plate which is, of course, connected to ground through the load, but doing this will also reduce the AC separation sought between Screen Grid and Plate - taking us back to conventional triode connection and the less than ideal Screen Grid operating parameters.

A useful addition is a small bypass capacitor (say 100 pF) shunting the Screen Grid voltage dropping resistor to eliminate any stray RF.

2. TRIODE OPERATION WITH SILICON DIODES

A significant practical improvement may be gained by installing a silicon diode between the Plate and Screen-Gird in the manner described in my OPTIMISED ELECTRON STREAM © TECHNOLOGY page - ie with the arrow pointing towards the Screen-Gird - instead of connecting the Screen Grid directly to the Plate, as is the conventional practice.

It offers the same benefits as in tetrode/pentode connection by removing Screen Grid output signal from the Plate circuit - ie the Tetrode or Pentode in Triode connection behaves like a real Triode, with electron flow direct from Cathode to Plate, as if the Screen Grid did not exist.

This configuration enables us to use beam power tubes, with all their benefits, as straight triodes, thereby attaining all the benefits of beam power tube operation but with the tonal and distortion qualities of triode operation.

The Grid Stopper resistor and/or Screen Grid voltage dropping resistor must still be kept in the circuit to control DC voltage behaviour because in triode connection there is far too much DC on the Screen Grids than is needed to do their job. In this case, less is thus better than more.

Some adjustment may need to be made to the Grid #1 bias voltage to limit Plate current to the design value.

Experiments I have undertaken in this area have resulted in substantially improved high-frequency performance, more natural sound and superior tonal characteristics compared with the conventional approach.
In my opinion, the most likely candidates for triode connection with silicon diodes feeding the Screens are the:

- **6AQ5** (275 VDC) 7 pin
- **6V6GT** (275 VDC) Octal
- **6CZ5/6973** (285 VDC) 9 pin
- **5881/6L6GC/7027A** (400 VDC) Octal
- **KT88** (550 VDC) Octal
- **813** (1100 VDC) Giant 7 pin

All are well proven fine quality beam power tubes, each famous in its own right.

Most other tetrodes, pentodes and beam power tubes have too low a Screen-Grid voltage rating to be suitable for triode operation at full rated Plate voltage.

There are many fine tetrode, pentode and beam power tubes that can be used in triode operation, however care is necessary to avoid applying excessive voltage to the Screen-Grids - such as the **EL34/6CA7** (425 VDC) (Octal) and **EL84/6BQ5** (300 VDC) (9 pin) pentodes.

Note: In high power applications - ie more than 100W RMS, transmitting triode tubes such as 805, 809, 810, 811, 812, 833, 845, 8000, 8005, etc may be a more economical and practical solution than pursuing a triode connection configuration with tetrodes or pentodes because of a wider choice of suitable tube types and characteristics, simplified wiring and power supply requirements. Most large tetrodes and pentodes have a relatively low rated Screen-grid operating voltage, indicating a high risk of problems when connected as triodes.

At the present time, large NOS triodes generally cost about the same as large NOS tetrodes or pentodes offering equivalent power output.

### 3. TRIODE OPERATION USING THE SCREEN GRIDS AS THE CONTROL GRID

This mode of operation offers yet another alternative for the application of Pentodes, Tetrodes or Beam Power Tubes as Triodes.

The method is simple.

Connect the Control Grid #1 to the Cathode

Use Grid #2 as the Control Grid.

This approach requires substantially higher DC negative bias voltage and considerable AC drive signal input voltage than as per the standard configuration, but offers the benefit of allowing full rated Plate Voltage to be applied.

This is because the Screen Grid does not attract electrons - in fact it is negatively charged so cannot.

Power output should thus be similar to that obtainable in Tetrode or Pentode mode - but with the tonal characteristics of Triodes. This is because the tube is now a real triode - ie only 3 effective elements (Cathode, Control Grid and Plate).

I am unable to provide details of typical operating conditions but this method has been used in professional broadcast standard equipment and in theory should be more reliable than the standard approach.

Class AB2 or B with fixed bias is essential for high Plate circuit efficiency and dynamic performance.

If you have experience with this configuration please advise your results.
Please let me know if you can add to this body of new knowledge and I will add it to this commentary.

Of course the smart thing to do here is to use tubes that are already triodes - instead of messing about with compromises - but then none of the triodes are beam tubes and thus do not offer the benefits of beam tube technology.

Also most of us have a junkbox stock of perfectly good Tetrodes, Pentodes or Beam Power Tubes just waiting to be used - so it is a tough call.

**REMEMBER:**

- ALWAYS TAKE CARE WHEN WORKING WITH HIGH-VOLTAGE -

  DEATH IS PERMANENT!!

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For suggestions, critique or discussion re this page contact:

Dennis Grimwood
SCREEN GRIDS in AUDIO and RF MODULATOR POWER TUBES

1. INTRODUCTION

Traditionally, the design of audio amplifiers has followed fairly clear and well established design principles.

Some of those principles relate to the way in which Screen Grids are used to control current flow in audio amplifier tubes, particularly power tubes.
Examination of professionally designed commercial circuits spanning more than 60 years' audio technology shows us there has been very little innovation in the way in which Screen Grids are used - ie little variation in, or departure from, conventional, traditional Screen-Grid application design concepts.

It is understandable why this is so, because innovative engineering was not encouraged in the consumption driven expanding global marketplaces of the 1940's through 1970's.

The post WWII market - ie the 50's and 60's era - was one of explosive growth and expansion in consumer and industrial demand, so it was primarily a seller's market. The market's natural wariness towards "way out" designs was high, so unconvention was not generally pursued. Few equipment manufacturers were brave enough to vary from the tried and true. Thus the prevailing audio design ethos was to "follow the leader".

In any event, unconvention often resulted in premature component failure, bad reputation, consumer wariness or rejection, and typically accompanied by an increase in manufacturing cost - and therefore selling price, with little perceivable benefit to the consumer.

Furthermore, programme materiel available to the consumer ex radio, phono or tape was generally of such quality that even the "critical listener" consumer was unable to discern audible differences between "good" and "superior" amplifiers.

Numerous documented scientific experiments since the 1930's demonstrated that most listeners were unable to discern the difference between a live and recorded performance from behind a screen. To the masses, there was no difference, so why pay more?

Audio amplifier equipment design became more or less a "variation on the theme" exercise in applications engineering, in much the same way as we now see design technology expressed in the configuration of CD players, DVD players and personal computers.

**Vacuum Tubes in Amplifiers:**

A very critical factor in tube amplifier design is the vacuum tube itself.

Electron tube manufacturing tolerances and acceptance test specifications are fairly wide, particularly in some types such as large power tubes, resulting in an audio amplifier design requirement for individual tubes to be individually adjusted, or "tuned" to specific circuit parameters for optimum performance - such as in high-power push-pull applications.

However amplifier manufacturers were reluctant to incorporate simple user adjustments into their products because that tempts (and provides the means for) the curious user to "play" with optimising controls such as Grid #1 bias or Grid #2 regulated supply, thereby ensuring poor performance, overheating, premature failure, or even self-destruction of the amplifier. Extra optimising adjustments also add considerable manufacturing cost to a base product, imply the amplifier is "dicky" or "temperamental", reduce reliability, and may offer the end user no real perceptible benefit apart from setting up the product to do what it is supposed to do in the first place and what alternative products do (or appear to do) without adjustments.

Although the absence of adjustments may lead to less than optimum performance, it does generally provide the consumer with a more reliable piece of equipment. One disadvantage, commonly found in parallel-push-pull amplifiers, is that 4 tubes or more may be supplied by a common bias supply, necessitating carefully matched tubes for reasonable dynamic performance and reliability. However, this arrangement ensures that whenever a single tube requires replacement, all four must be replaced together to preserve balance. During the 1950's thru 1980's, obtaining an accurately matched set of tubes was often a challenging task.

However in the long run, this simplified approach to tube selection provided the preferred choice for a safe solution and equitable warranty protection to both manufacturer and user.

Since the 1950's, the choice between cathode bias or fixed bias was often determined by the lower manufacturing cost of cathode bias and the self-protecting effect of cathode bias, so fixed-bias tended to be used only where high power was needed such as in public address or guitar amplifiers.

*Cathode-bias* was a natural evolution from the "back bias" used widely in early radio receivers, where the field coil of the loudspeaker served both as a filter choke and a convenient DC bias ("C" supply) voltage source. When the field-coil loudspeaker was replaced by the cheaper to manufacture "permanent magnet" style loudspeaker around the early 1950's, back-bias designs more or less disappeared from the face of the earth.

*Back-bias* requires more complex wiring than cathode-bias so it was seen as an unnecessary complication to wiring costs, for no realisable benefit to the end user.

*Cathode-bias* also offers inherently higher reliability than back-bias or fixed-bias, as well as providing a self-compensating...
These "improvements" resulted in a performance situation where some amplifiers and components, relying on the feedback to restore performance to an acceptable standard, provide even poorer power supplies and driver stages, because audible hum could not be heard. The advent of loop negative feedback - ie negative feedback from output to input - further assisted some manufacturers to performance.

Least two tubes in push-pull, resulting typically in tube mismatch - ie still requiring a matched pair of tubes for optimum performance.

Loop negative feedback also facilitates the use of poorer quality lower-cost output transformers and wider tolerances on tubes and components, relying on the feedback to restore performance to an acceptable standard.

These "improvements" resulted in a performance situation where some amplifiers with feedback performed no audibly better than earlier design amplifiers without feedback - except under steady state conditions on the test bench into constant resistive loads.

The later introduction of silicon rectifiers and voltage doubler power supplies enabled further cost-reduction at the expense of transient performance. Advantages such as substantially improved power supply regulation gained from silicon rectifiers over tube rectifiers were soon offset by cost-saving measures.

The traditional filter choke was an early casualty of cost reduction. Good quality 1940's and 1950's amplifiers used a full-wave rectifier and a two stage choke input filter, however this progressively degenerated to the point where many popular amplifiers of the 1970's had a voltage doubler power supply with no filter choke at all, relying on the combined effects of larger electrolytic filter capacitors, loop negative feedback, and push-pull hum cancellation to produce an acceptable product.

Very few amplifiers included regulated power supplies for their Screen-Grids, because of increased manufacturing cost. Although the RCA Receiving Tube Manuals published schematics incorporating Screen-Grid regulation, the most common configuration was that the Screen-Grids were fed directly from the B+ supply - ie at high-voltage, often without any Grid-stopper resistor. One variant was to use a dropping resistor and filter capacitor, from the B+ to supply the Screen-Grids, but this arrangement results in poor Screen-Grid voltage regulation, with attendant drop in performance.

In other words, in an attempt to hold-down manufacturing costs over time, some tube amplifier manufacturers actually took the audio industry backwards in terms of performance evolution.

So, apart from the highly acclaimed triode connected Williamson (D.T.N. Williamson 1947 and 1949), followed by the magnificent tetrode connected U.S. McIntosh (F.H. McIntosh and G.J.Gow 1949) and later (but much inferior) U.K. Quad II (1953) amplifier, with their "unity coupling" power output stage, and the original Ultra-Linear (D. Hafler and H. I. Keroes of Acro - 1951) design; there is little to show for 60 odd years of progressive global technological evolution in tube audio.

Note: History shows the term "ultra-linear" was developed by Hafler and Keroes to define their specific configuration based upon the original 1936 British Patent of A.D.Blumlien, which was fairly generic in respect to transformer ratios. It appears that his innovative design was neither refined nor exploited commercially during the 14 year life of his patent, noting the British Quad II amplifier of 1953 bypassed this opportunity, however some researchers suggest it had previously been used in Australia as far back as 1933 - a fact that if true would have invalidated his patent. Perhaps the military demands of the WWII years diverted Mr. Blumlien's attention to his prolific innovative design activity covering a wide range of other technologies and the ultra-linear concept was left to others to further develop and exploit - however audiophiles remain indebted to his contribution. The wheels of technological progress sometimes turn slowly!!

It is relevant that all these designs relied heavily for their final performance upon extremely high quality output transformers - in the case of the McIntosh, bifilar windings (primary and secondary windings were wound together with no insulation between them or between layers, requiring very high quality winding wire and winding techniques) and fully potted construction were featured (a remarkable engineering achievement) - so manufacturing expense increased substantially in any event.

Despite the current raves for single-ended push-pull concepts, commercial attempts to exploit that particular technology inevitably failed in preference to convention. One approach by the Dutch Philips group in the 1960's, used an output-transformerless (OTL) single-ended push-pull amplifier connected to an 800 ohm Philips loudspeaker, requiring the consumer to purchase a complete system from the one supplier - not a popular concept for modular hi-fi component buyers (particularly those who already owned a fine set of loudspeakers), thus relegating this new technology to the mass consumer market - thereby destroying its appeal to the audiophile. This technology faded into obscurity along with demise of the "radiogram" all in one system.

Inevitably, all attempts to depart from proven simple audio circuit design principles resulted in increased cost, reduced reliability, increased downtime and service costs, and consumer anger.

The realities of global markets and a long way to a competent service shop resulted in manufacturers being forced by
circumstances to limit their experimentation - or experiment to discover that alternatives to conventional design simplicity were not commercially viable products. Most manufacturers were limited to sourcing components from a small pool of suppliers so manufacturing costs were similar across the industry. Designs had to be both simple and cost-competitive.

Top Cap Tubes:
Another factor that produced suppression of innovation was the swing away from tubes for audio applications that incorporated top caps for their plate, or anode, connection.

Users often found themselves “zapped” when changing a tube, by inadvertently touching the cap lead or terminal - particularly if the amplifier was switched on - a most unpleasant experience.

Long Plate leads also present problems with induction to and from nearby components, stray RF pickup, output stage instability, transformer mechanical construction and chassis layout.

Although widely used in professional broadcast and public address applications during the 1940's and 1950's, top cap style tubes - such as the 6146/QE05-40, 6DQ6A, 6CM5/PL36, 5B/254M, and the great 807, have not been popular for hi-fi or guitar amplifier applications - the largest commercial market segments for tube use in applications greater than about 5 W RMS output. Thus this style of tube, which offers considerably higher power outputs than no-top-cap standard octal socket styles, or all glass 9 and 12 pin tube types (eg 7868), has been little used after 1955 in hi-fi and guitar amplifier designs (although still extensively used in television receiver applications until the 1970's).

This pragmatic design philosophy forced tube manufacturers to develop tubes that produced more power from a conventional (usually octal based) tube having no top cap - in a valiant effort to put amplifier performance back to where it had already been. Result - the EL34/6CA7 and KT88, both practically limited by the dielectric strength of the octal base and socket to about 600 VDC B+ supply - but both needing high Grid #2 ratings to offset the limited plate voltage as a means to retain adequately high power output.

It is of interest that the KT88 is identical to the TT21 transmitting tube, which has a rated Plate Voltage of 1.25 kV applied to the top cap connection. In the KT88, the Plate connection is relocated to the octal base. This modification results in a maximum rated Plate Voltage of 600 VDC for the KT88.

For 250 to 300 VDC supplies, there are also the EL84/6BQ5/7189, and the 6V6GT, 6AQ5/6HG5/6005 and 6CZ5/6973 families.

However, in all these types, analysis of manufacturers’ data shows the proportionately high Screen Grid voltage needed to obtain maximum power output results in substantially higher harmonic and intermodulation distortion than seen in conventional RF beam power tubes combining high plate voltage with relatively low Grid #2 voltage for the same audio output power- eg typically 4 to 5% instead of 1 to 2% THD without negative feedback.

The suitability of the EL34/6CA7 and EL84/6BQ5 to ultra-linear connection offsets this disadvantage somewhat, albeit at reduced power output, but the original 6L6 family are not so fortunate being practically limited by their lower Grid #2 rating.

The original GEC KT88 thus became the only tube to offer a reasonable solution, providing up to 100 W RMS per pair, however they were expensive, of widely varying quality, required substantial free-air space for ventilation, supporting componentry and circuitry of professional broadcast standard, and were really a little large for an octal socket to support. Being heavy, the KT88 is not suited to inverted mounting (eg guitar amplifiers) without supporting straps to prevent them falling out of their sockets. However from the outset (about 1960), transistor amplifiers were easily able to match this performance (on paper) in a substantially cheaper, smaller, lighter and more reliable package, so the KT88 was soon displaced in the mass market.

In some industries that were high consumers of vacuum tubes, particularly in guitar amplifiers, there is also clear evidence that tube designs were enhanced to cater for limitations in the final product. That old favourite, the 6L6, has been upgraded over and over again, even though superior top cap versions (eg 807 and 1614) were available from the outset - albeit at significantly higher cost.

Manufacturing cost, profit margins, market share and sales revenue were each in their own right, powerful design engineering drivers and inhibitors.

Standard domestic quality driver tubes such as 6SN7GT, 12AT7, 12AU7A etc triodes and their popular pentode cousins, 6SJ7, 6AU6, 6U8 and EF86, have hardly changed throughout the 60 years since they were first released. Later improved "premium quality" versions rarely found their way into commercial audio amplifiers, primarily because they cost more, offered no detectable audible benefit to the listener, had electro-mechanical characteristics that provided in practice properties or performance only marginally different to the standard tube - if at all (eg rattles and microphonics in "premium" tubes), and frequently could not be replaced in the country of use - after all who wants a product that cannot be repaired or likely to be out of action for many months whilst waiting for an expensive imported tube to arrive? Not only that, but the replacement cost of a premium quality tube was often many times the cost of the equivalent standard type.
Summary:

So a review of commercial circuits shows that for the whole of that 60 year period between 1940 and 2001, only a few basic types of tubes were used in all the audio amplifiers ever produced in the whole world.

The result is that:

1. there is very little literature about Screen Grids
2. there are are few examples of innovative design variants
3. audio amplifier design standards reflected the need for simple tubes that could be overloaded and abused by users
4. audio amateurs - ie hobbyists and project builders - have had to remain within a very rigid published design framework
5. published manufacturer's tube data invariably fails to provide information about the effect of Screen Grid voltage upon Plate Current
6. there is little published manufacturer's data available for non-popular tube types
7. there is little practical knowledge available to facilitate experimentation with non-popular tube types
8. a self-destructing commercial approach manifested that inhibited innovation in the tube based audio equipment industry, paving the way for their displacement by semi-conductors

This page attempts to quantify some of the major principles and possibilities regarding improving vacuum tube technologies in the area of Screen Grids.

I do not claim it to have any technical expertise or validity whatsoever and am happy to be challenged in the interests of mutual learning. If you can add any information that will benefit the audio enthusiast please email it to me.

2. THE SCREEN GRID (GRID # 2) - PRIMARY FUNCTIONS

The Screen Grid is an extra element added to the basic three element configuration of triode tubes to form a four element configuration tube called a tetrode.

![Fig. 1: Graphical Representation Of A Tetrode Vacuum Tube](image)

The Screen Grid is also incorporated into multi-electrode tubes such as pentodes, heptodes and octodes.

The Screen Grid is assigned the functional title Grid #2, to indicate it is the second Grid from the Cathode.

The Screen Grid usually comprises a formed coil of wound turns of round wire, mounted physically concentrically between the Control Grid (Grid #1) and the Plate (Anode) in multi-electrode vacuum tubes and acts as an electrostatic shield between them.

The primary functions of the Screen-Grid are:

- to act as a screen. To perform this function, the Screen Grid is positioned between, thus separates or "screens", input circuits (Grid 1) from output circuits (Plate or Anode) within the tube, thus the name "Screen-Grid".
- to accelerate and attract electrons to the Plate
- to provide a means for additional control over electron flow
- to reduce Grid 1 to Plate capacitance and thereby improve frequency response, linearity and operating frequency
- to reduce Plate to Grid 1 feedback
- increase tube efficiency
- increase gain
- increase output voltage
- reduce distortion (compared to a Triode)
- improve linearity

The most important attribute of the Screen-Grid - but one that is not clearly explained in Tube Manuals - is that it becomes the primary ANODE in the tube - ie when the Screen-Grid is energised to a positive potential to the Cathode, the Plate becomes simply a passive collector of those electrons emitted from the directly or indirectly heated Cathode that have been attracted by, and passed through, the Screen-Grid to it.

The RCA 1937 Receiving Tube Manual tells us this way at Page 9:

"The Screen is operated at a positive voltage and, therefore, attracts electrons from the Cathode. But because of the comparatively large space between the wires of the Screen, most of the electrons drawn to the Screen pass through it to the Plate. Hence the Screen acts as an electrostatic force pulling electrons form the Cathode to the Plate."

Thus when a Screen-Grid is present, IT is the ANODE and the Plate becomes a secondary or pseudo-anode only.

Understanding this fundamental design feature is crucial to understanding the significance of maximum Screen Grid rated voltages and their relationship to Plate voltages in all cases for triode, tetrode, pentode, beam power tube or ultra-linear configurations.

The first tetrodes were introduced to enable stable amplification at radio frequencies - ie to shield the anode from the grid. As the screen was at ground potential for signal frequencies whilst slightly increasing the input and output capacities the grid plate capacity was reduced to the point that neutralization was completely unnecessary.

However if the anode was operated with a voltage of less than the screen, dynatron oscillations could occur - which led to the introduction of the suppressor grid, the function of it being to repel secondary emitted electrons back to the anode rather than allowing them to be attracted back to the screen when its potential was less than the anode.

In output valves the evolution of the tetrode / pentode was needed for completely different reasons. As efforts were made to increase the amplification by altering the tube geometry the resistance of the tube to DC went up, so the addition of the screen grid enabled the anode current to be relatively independent of the anode voltage. This fact did however dramatically increase the AC resistance, which is not always a desirable result for an audio amplifier.

In some types of tetrodes and beam power tubes the Screen-Grids are positioned in-line with the Control-Grid (ie in-line with or behind the electron beam) and this configuration is described as "aligned Screen-Grids" - eg 6L6GC.

However in many types of pentodes and beam power tubes the Screen-Grid is not aligned and this configuration is described as "unaligned Screen-Grids" or "non-aligned Screen-Grids" - eg EL34. (Some users report that the early Philips EL34's had aligned Screen Grids, whereas later production ex other manufacturers were unaligned, resulting in increased tube failure and decreased performance - food for thought.)

In some electron tube designs, the coil is wound round and in others it is wound flat. Generally speaking, tubes having round - ie cylindrical - Plates would have Screen Grids wound on a round former, and tubes having rectangular Plates would have Screen Grids wound on a flat, or rectangular, former. This results in an arrangement whereby the Screen Grid is generally parallel with the conducting (electron collecting) portion of the internal Plate surface and the conducting (electron emitting) surface of the Cathode.

The usual arrangement is for the turns on the Screen Grid to be evenly spaced, however sometimes variable spacing is used for particular effect - such as in "remote cutoff" tubes.

Of importance to this paper is the physical spacing, pre-determined during manufacture, between the Cathode (negative terminal of the tube) and Screen Grid, and Screen Grid to Plate (positive terminal of the tube) - ie the relative positioning of the Screen-Grid between the cathode and anode of the device.

Philips introduced the penthode - (as that is how they spelt it) - but Mazda played with a critical distance tetrode or, as they referred to it, a "kinkless tetrode", which works as per the description of a beam tetrode which, as a result of aligned grids and beam forming plates, simply concentrated the cloud of electrons which behaved as a suppressor grid. (this contribution thanks to Denis Cook)

The spacing between the grid and screen determines the ability of the screen in determining the characteristics of the tube. The screen anode spacing is also of great importance in that it determines the location of the space in which the electron stream is moving slowest and is therefore most concentrated so to act best as a virtual suppressor.
It is relevant to the concepts presented in this paper that in the case of directly heated filament tubes - ie where the Filament is the Cathode - for practical manufacturing and cost control reasons the diameter of the Filament wire is usually the same as that of the Screen-grid. However the length of the Screen-grid wire is usually substantially more than that of the Filament. This means that the electron collecting surface of the Screen-grid is substantially greater than that of the electron emitting surface of the Filament/Cathode. Consequently the Screen-grid has the capability to collect significant numbers of electrons emitted by the lesser surface area Filament.

RCA Transmitting Tube Handbook TT-4 at pages 7 and 8 explains the function of the Screen Grid in this way:

"When a tetrode is used as an amplifier, the Screen Grid is operated at a fixed positive potential (usually somewhat lower than the Plate voltage), and is bypassed to the Cathode through a capacitor having very low impedance at the operating frequency. This capacitor diverts signal frequency alternating currents from the Screen Grid to ground, and effectively short-circuits the capacitive feedback path between Plate and Control Grid.

The Screen Grid acts as an electrostatic shield between the Control Grid and the Plate, and reduces the Grid-Plate capacitance to such a small value that internal feedback is usually negligible over the range of frequencies for which the tube is designed.

Because the Screen Grid is operated at a positive potential with respect to the Cathode, it collects a substantial number of electrons and, therefore, reduces the Plate current which can flow at a given Plate voltage.

The addition of a Screen Grid thus increases the internal resistance, or Plate resistance of a tube. However, it also gives the Grid No. 1 a greater degree of control over the Plate resistance, and thus increases the voltage amplification factor.

The voltage at which the Screen Grid is operated has a substantial effect on the Plate Current of a tetrode.

This characteristic makes it practicable to control the gain of a tetrode by variation of the DC Screen Grid potential, or to modulate the tube output economically by the application of a signal voltage to the Screen Grid - as well as to the Control Grid.

It is usually necessary, therefore, to remove ripple and other fluctuations from the Screen Grid supply voltage to prevent undesired modulation of the tube output."  (End quote)

SVETLANA say: "Regular tetrodes are rarely used for audio applications because of an effect called "tetrode kink", caused by secondary emission. Most of it is due to electrons bouncing off the plate, some from the screen."

3. RELATIONSHIP BETWEEN PLATE CURRENT AND SCREEN-GRID CURRENT

It is important to understanding Screen-Grid function that one more aspect be considered for the case of POWER TUBES.

Compared with a Triode, the addition of the Screen-Grid to a Tetrode, Pentode or Beam Power Tube, dramatically changes the electronic behaviour of the Power Tube.

The characteristics of a TRIODE POWER TUBE are illustrated in the following graph for the 6BQ5/EL84 Power Pentode connected as a Triode and having a Plate and Screen-Grid Voltage of 300 VDC.
In a POWER TRIODE the Plate Current is directly proportional to Plate Voltage.

In a POWER TRIODE the Plate Current is directly proportional to the Grid #1 (Control-Grid) Voltage.

In normal POWER TRIODE amplifier applications, the Plate Voltage is fixed by the B+ supply, hence the Plate Current (and therefore power output) will vary in direct proportion to changes in the Control Grid Voltage (i.e., input drive AC signal). This has the effect that small changes in signal voltage produce large changes in Plate Current.

It also has the effect that in push-pull TRIODE POWER TUBE applications, BOTH tubes must be accurately matched by selection, test and Control-Grid Bias Voltage adjustment, to ensure both tubes amplify equally in the push-pull pair. Minor performance differentials between tubes will produce marked results in the amplifier output signal - a good case for single-ended TRIODE operation.

In an POWER TRIODE, careful examination of the Plate Current curves shows most POWER TRIODE amplifiers suffer from non-linearity between low and high signal input AC drive voltages. As Grid #1 voltage increases it causes the Plate Current to increase very rapidly, causing the Plate Voltage to decrease (by AC and DC losses in the output transformer windings and rectifier circuit), resulting in loss of peak power at the crest of the signal voltage - i.e., transient signals are diminished in magnitude by the output stage.

The above graph clearly shows that for any given value of Plate Voltage, the negative swing in signal voltage applied to Grid #1 will produce a different change in Plate Current to that produced by an equal swing in the positive excursion. This is why Class A amplifiers must use a value of Grid #1 voltage that is sufficiently high (less negative) to enable reasonably equal positive and negative Plate Current swings, whilst keeping within permissible Plate Dissipation limits.

It will be also observed that during the negative swing of the signal voltage, the more the Control Grid (Grid #1) swings negatively, the less linearly Plate Current follows changes in Grid #1 voltage.

Such requirement inherently introduces some challenges in TRIODE POWER AMPLIFIER design and component selection - particularly in Class A designs.

On the other hand, the addition of the Screen-Grid to create a Tetrode, Pentode or Beam Power Tube, dramatically changes the electronic behaviour of the Power Tube insofar as Plate Current is no longer dependent upon Plate Voltage.

Graph Courtesy of Philips Miniwatt Electronics Handbook (1960).
The characteristics of a **TETRODE, PENTODE OR BEAM POWER TUBE** are illustrated in the following graph for the 6BQ5/EL84 Power Pentode connected as a Pentode and having a Plate and Screen-Grid Voltage of 300 VDC.

Please note this is the same tube and same applied voltages as shown in the above graph - just configured differently.

![Graph Courtesy of Philips Miniwatt Electronics Handbook (1960).](image)

The Plate Current curves for a Tetrode, Pentode or Beam Power Tube show that Plate Voltage can fluctuate markedly but does not affect Plate Current at all. So long as the Plate Current responds to the AC signal drive voltage applied to Grid #1, then the tube will produce a linear response to that signal.

The one requirement for this condition to be realised is that the Screen-Grid voltage be relatively constant, hence amplifier designs using a common B+ supply to both Plate and Screen-Grid inherently lose some of the aforementioned attributes of Screen-Grids.

This characteristic of Tetrodes, Pentodes or Beam Power Tubes offers tremendous options and benefits to the amplifier designer.

Because POWER OUTPUT is calculated as the square of the output voltage divided by the load impedance, provided Screen Grid voltage remains constant and Grid #1 Voltage is adjusted for correct zero signal idle current dissipation, power output may be increased dramatically by the simple device of increasing the Plate Voltage - ie within practical limits, the driver stages can be the same for more or less any configuration of Tetrode, Pentode or Beam Power Tube output stage.

That is to say, provided negative loop feedback is not used from the loudspeaker, any front-end can be matched to any power stage - a most beneficial situation for the home constructor.

It will also be observed from Plate Current curves, that Tetrode, Pentode or Beam Power Tubes are generally more linear between minimum and maximum AC drive signal conditions - particularly at the low-signal voltage end of the scale. Most high-fidelity audio amplifiers are operated at low volume in the home hence tube behaviour at the lower end of the Grid #1 voltage range is a critical issue - because the sound so produced is what the discerning listener hears.

On the other hand, public address amplifiers, guitar amplifiers and broadcast transmitters tend to be used at or near their maximum output, so more interest is in the neahaviour of tubes under full output conditions (where other challenges face us).
Finally, it should be noted that when a Tetrode, Pentode or Beam Power Tube is configured by wiring to "Triode Connection", then it will behave as a Triode, with all the shortcomings (and benefits) of Triode operation.

******************************************************************************************************************************************************

To consider how the Screen-Grid affects Plate Current as described above, let us examine implications of the above statement from RCA that: "Because the Screen Grid is operated at a positive potential with respect to the Cathode, it collects a substantial number of electrons and, therefore, reduces the Plate current which can flow at a given Plate voltage. The addition of a Screen Grid thus increases the internal resistance, or Plate resistance of a tube." (end quote).

This is a little researched subject because in practical audio applications this relationship has been more or less of little concern to audio amplifier designers.

However it does matter.

Tetrode and Pentode connected amplifiers always supply the Screen-Grids either from the Plate Supply (B+) or a separate Screen-Grid supply, hence Screen-Grid Current is not usually a major consideration to amplifier designers - simply because Screen-Grid current needs are easily met by the power supply.

There is a direct relationship between Plate Current and Screen-Grid Current which we must be aware of if we want to build better amplifiers.

The following graph, courtesy of Philips Miniwatt, illustrates this very clearly.
This rare original manufacturer's graph clearly shows us that under fixed conditions of constant Plate Voltage and Screen-Grid Voltage, both Plate Current and Screen-Grid Current increase or decrease in response to change in Grid #1 Voltage.

That is to say Grid #2 Current is just as much affected by a change in Grid #1 Voltage as is Plate Current.

Thus Plate Current and Screen-Grid Current are a direct function of Grid #1 Voltage. This characteristic is typical for all audio tetrodes, pentodes and beam power tubes.

However, the relationship between Plate Current and Screen-Grid Current is not linear.
In this case it can be seen that at -30 V Grid #1 bias, the Screen Grid Current is 1.7% of Plate Current, whereas at -20 V bias is 1.9%, at -10 V bias is 2.5%, and at 0 V is 3.3% of Plate Current.

These relativities could reasonably expected to be different with other values of Plate Voltage and Screen Grid Voltage.

Although these differences may appear small, they tell us the tube is more efficient in Class A than in Class B, because the Screen-Grid Current is a smaller portion of total current (Plate Current + Screen-Grid Current) in Class A (low Grid #1 Voltage) than in Class B (high Grid #1 Voltage).

This phenomenon will be exacerbated by further changes in Grid #1 bias Voltage caused by the flow of Grid Current, such as in Classes AB and B.

In other words a higher proportion of the electron stream reaches the Plate in a Class A amplifier than in a Class B amplifier.

This means that in an amplifier having characteristics that produce a variable Grid #1 Voltage there will be some offset to the reduced power output resulting from reduced B+ supply voltage by the increased tube efficiency resultant from the change in Grid #1 Voltage.

For example, where an amplifier has a single common power transformer supplying the whole of its power needs, increased total current under peak signal conditions will cause reduced Grid #1 Voltage (from poor power supply regulation).

Note however, that the Philips Miniwatt 6KG6/PL509 video pentode shown above is not typical of audio tetrode, pentode and beam power tubes - a point demonstrated by reference to "typical operating conditions" published in Manufacturers' Tube Handbooks. These show that in a typical beam power tube, the Screen Grid current at maximum signal power is around 20% of Plate current. This ratio of currents appears to be largely independent of Plate voltage.

It would therefore be reasonable to assume that up to 20% of prospective signal power is lost in the Screen Grid circuit in a conventional amplifier.

(Note: Two notable exceptions are the 807 and 814 beam power tubes that incorporate advanced design technologies to increase tube efficiency and reduce distortion, however in the overall sheme of things this technology appears to have been limited to these two tube types - if you are aware of others please let me know)

The functional relationship between Plate and Screen-Grid is further illustrated by Radiotronics Magazine #90 of September 1938, which provides data for a pair of type 6L6 tubes operating as a beam power tube in push-pull Class A1, for an operating condition having a common Plate and Screen Grid DC supply voltage.

This shows:

<table>
<thead>
<tr>
<th>Plate and Screen Volts</th>
<th>100</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>290 (max)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero Signal Plate Current mA</td>
<td>32.5</td>
<td>55</td>
<td>85</td>
<td>120</td>
<td>150</td>
</tr>
<tr>
<td>Max. Signal Plate Current mA</td>
<td>37.5</td>
<td>65</td>
<td>100</td>
<td>140</td>
<td>175</td>
</tr>
<tr>
<td>Zero Signal Screen Current mA</td>
<td>2.5</td>
<td>4.5</td>
<td>7</td>
<td>10</td>
<td>12.5</td>
</tr>
<tr>
<td>Max. Signal Screen Current mA</td>
<td>4.2</td>
<td>7.4</td>
<td>11.4</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>Grid #1 Bias V</td>
<td>-6.25</td>
<td>-9.5</td>
<td>-12.75</td>
<td>-16</td>
<td>-18.5</td>
</tr>
<tr>
<td>Load resistance P/P ohms</td>
<td>8000</td>
<td>6500</td>
<td>5600</td>
<td>5000</td>
<td>4600</td>
</tr>
<tr>
<td>Power Output Watts RMS</td>
<td>1.6</td>
<td>4.2</td>
<td>8.4</td>
<td>14.5</td>
<td>21.2</td>
</tr>
</tbody>
</table>

Notice how much power output changes when the Plate and Screen Grid voltages drop from 290 to 250 - a likely situation with a tube rectifier power supply - see rectifier forward voltage drop characteristics in manufacturer's tube handbook data.

A significant improvement to power supply regulation can be made by the simple change to full-wave silicon diode bridge rectifier, and preferably the inclusion of at least one filter choke, which leaves only the power transformer regulation to deal with.

Notice also how the ratio of Screen Grid current to Plate current changes between zero and maximum signal and between different operating voltages. This translates into non-linearity.
Plate Current - Control Capabilities of the Screen-Grid:

Let us also examine implications of the statements by RCA that:

"The voltage at which the Screen Grid is operated has a substantial effect on the Plate current of a tetrode." (RCA Manual TT4)

"As long as the Plate voltage is higher than the Screen voltage, Plate Current in a Screen-Grid tube depends to a great degree on the Screen voltage and very little on the Plate voltage" (RCA Manual RC14)

Beyond the above basic design criteria, little discussion is offered in manufacturers' tube handbooks regarding the effects of Screen-Grid voltage on Plate current.

The approach generally taken is to promote the application and use of vacuum tubes by publishing "typical" operating conditions for vacuum tubes, including recommended Grid #2 operating voltages.

In the case of audio tubes there are copious examples provided that cover likely popular uses - often taken by designers verbatim or as recommended by tube manufacturers, without researching alternatives - resulting in copycat, "more-of-the-same" designs. After all, why go the trouble and expense of researching something that someone else had already pre-determined and/or recommended - particularly if that "someone" has the expertise of a tube manufacturer?

Curves are nearly always provided for Control Grid (Grid #1) modulation characteristics, but no so for Grid #2.

Hence little published data is available to demonstrate the effects upon Plate Current from varying Grid #2 voltage.

A complicating, and perhaps confusing, factor is that tube manufacturers often recommend for "typical" applications, the same Screen Grid voltage for a very wide range of Plate Voltages - particularly evident in high-voltage transmitting tubes.

There has also been no explanation as to why - except in the case of a small group of audio tubes - tube manufacturers typically recommend Screen-Grid operating voltages that are mostly only around only half their maximum Screen-Grid rated voltage - irrespective of applied Plate Voltage.

However one remarkable graph was published way back in 1957 that provides us with a deep insight into Screen Grid behaviour, and is reproduced here for your information.

![Fig: 3 - Philips Miniwatt 6CM5/EL36 Power Pentode for Audio and Video Applications](image)

This remarkable rare original manufacturer's graph, shows very clearly the influence that Grid #2 voltage (Vg2) has over Plate Current (Ia).
In this case, Grid #1 voltage (-1 VDC) has been selected to ensure it has negligible control over Plate Current, thus making Grid #2 the controlling electrode. (In this tube Grid #1 voltage would normally be set at up to -29V to control Plate Current.)

This graph clearly shows that **Plate Current is a direct function of Grid #2 Voltage**. It is typical for all audio tetrodes, pentodes and beam power tubes.

This graph also clearly shows that Plate Current is not a function of Plate Voltage in the useable range of Plate Currents - ie Plate Current is linear and very dependent upon Grid #2 voltage in a reasonably linear relationship within the boundaries of operation determined by the maximum **plate dissipation** rating.

It follows that the absolute limiting parameter of **plate dissipation**, although the product of Plate Voltage and Plate Current, is directly determined by Grid #2 voltage - in other words, overheating or self-destruction of the tube may easily be achieved by excessive Grid #2 voltage.

This graph shows very clearly why we should be concerned with the Screen Grid operating voltage and to take extra care that it will be set at a value that will not only provide optimum performance but also extend tube life by ensuring tube dissipation is within the prescribed limits.

Armed with the design knowledge provided by this graph, together with further analysis discussed below, we can make some determining assumptions regarding the design of appropriate operating conditions for Screen-Grids.

### 4. PRIMARY FUNCTIONS OF THE SCREEN-GRID

Thus, the primary functions of the *Screen Grid* in an Electron Tube are to:

a) create an electrostatic shield between the Control Grid and the Plate  
b) minimise capacitance between the Control Grid (Grid 1) and the Plate  
c) control the electron flow in such a way as to make Plate current practically independent of Plate voltage over a certain range of circuit parameters  
d) control **plate dissipation**  
e) increase tube amplification and, in the case of a power tube, increase power output  
f) prevent feedback between the Control Grid and the Plate  
g) prevent unwanted oscillations of one type or another  
h) focus and accelerate the electron flow from cathode or filament to plate  
i) control electron flow to an extent more than that available from a single grid tube

In RF applications the screen grid may also be used to modulate the tube.

A further consideration is the **mutual characteristic** of a tube.

This term describes the **inter-relationship** between Control Grid voltage and Screen-Grid voltage and their combined **mutually interactive** effect upon Plate Current.

*To maintain Plate Current at a constant value*, it is necessary to increase (ie make more negative) Grid #1 voltage to offset an increase (make more positive) in Grid #2 voltage. The converse effect applies - ie decreasing Control Grid voltage (more positive) requires a reduction (more negative) change to Screen Grid voltage.

The **mutual characteristic** is important to optimising operating conditions within the tube’s maximum Plate and Screen Grid dissipation ratings.

The following rare graph, which defines **mutual characteristic** for the **ITT-Standard Type 4X150A Beam Power Tetrode**, courtesy of ITT-Standard publication MSE/123 published 1963, illustrates this phenomenon.

This graph clearly illustrates the inter-relationship between Control Grid, Screen-Grid and Plate with the variables being Grid #1 and Grid #2 voltages.

It also shows that to limit Plate Current to safe or permissible values, it is essential to reduce Control-Grid voltage as the Screen-Grid voltage moves closer towards the Plate voltage.
THEORETICAL APPROACH

For those who are theoretically minded, there is an excellent article on Screen Grid behaviour at [http://www.burle.com/cgi-bin/byteserver.pl/pdf/tp122.pdf](http://www.burle.com/cgi-bin/byteserver.pl/pdf/tp122.pdf)

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5. SCREEN GRID (GRID # 2) - DC SUPPLY

The Screen Grid therefore, when connected for tetrode, pentode or beam power tube operation, should always be supplied by a suitable low voltage direct current supply, having a low-impedance path to ground - ie effectively AC earthed.

The screen-grid supply should be regulated - or have good regulation properties - and be independent to the plate B+ supply.

The screen-grid supply should be capable of supplying transient peak current sufficient to supply the screen-grids with adequate power to support transient signals - without incurring voltage drop at the screen-grids.

Voltage drop translates into significantly reduced gain in the tube, which translates into reduced transient peak power. Power decreases at the rate of the square of the voltage reduction divided by the load.
A full-wave silicon diode bridge rectifier circuit with choke input to filter and as much capacitance as is practicable - i.e. at least 1,000 uF but preferably 5,000 to 10,000 uF - is desirable to ensure the screen grid voltage remains practically constant regardless of AC signal level and consequent DC Screen current.

Better still, a double section filter, comprising choke input to filter, followed by a second choke and capacitor, will ensure a high quality DC supply.

Of course, a fully engineered regulated power supply is best to accommodate wide fluctuations in Screen Grid current.

**DC Supply - Essential Requirements:**

RCA Transmitting Tube Handbook TT-4 states:

- At p7: "it is usually necessary, therefore, to remove ripple and other fluctuations from the screen-grid supply to prevent undesired modulation of the tube output".
- At p17: "Hum caused by the presence of ripple in dc plate, screen-grid (Grid No.2), or bias (Grid No. 1) supply voltages, or by the use of ac filament or heater voltages, is also cancelled or substantially reduced in a push-pull stage."
- At p30: "Plate and screen-grid supply circuits for single-ended Class A power amplifiers must be well filtered to minimise hum and undesired coupling with other stages in the equipment."
- At p30: "serious distortion and inadequate power output may result on large input signals unless the plate and screen-grid supply voltages are well regulated and the bias is extremely stable."
- At p31: "For optimum performance, plate supply regulation for Class B and AB2 amplifiers should be within 5%, and screen-grid supply and grid-bias supply regulation should be within 3%.

At p73: "A bleeder resistor drawing about 10% of the total output current should be permanently connected across the output of the supply. Although this resistor reduces the maximum useful output current slightly, it prevents the output voltage from rising excessively when the external load is reduced, and thus improves regulation and provides a substantial measure of protection for the filter capacitors. It also discharges the filter capacitors when the equipment is switched off, and thus minimises shock hazards. Good regulation is desirable, even when substantially constant output voltage under varying load conditions is not a primary requirement."
- At p75: "In power supplies for cw transmitters, a ripple of not more than 5% is usually satisfactory. Power supplies for variable-frequency oscillators and phone transmitters generally should have ripple of 0.25% or less. Power supply ripple in high-gain speech amplifiers and receivers should not exceed 0.1% to prevent hum modulation of output signals. The most economical method obtaining ripple voltages below 1% is by the use of double-section filters."

Note that if the Screen Grid supply is obtained from the Plate supply, both Plate and Screen Grid voltages will drop simultaneously with high input signals, resulting in reduced power output, increased distortion and non-linearity - i.e. reduced transient response in reproduction.

**Effect of Plate and Screen Supply Regulation**

When all element voltages change at the same time due to poor power supply regulation the change in performance will be very audible.

The Radiotron Designers Handbook 3rd Edition (1940) at page 295 says:

"With a triode valve, the rise in average Plate current at full output (due to rectification) causes a decrease in the effective Plate voltage, due to the resistance of the B supply. The result is a comparatively slight reduction in power output, since the drop in Plate voltage opposes the rise in current."

With a Pentode or Beam Power Tetrode valve, however, the effect is much more pronounced. If the Plate and Screen operate at the same voltage from a common supply, the drop in Plate voltage due to the resistance of the B supply also causes a similar drop in the Screen voltage. This drop in Screen voltage results in a complete change in valve characteristics, the zero bias then being lower than with full voltage. The cut-off grid voltage is then lower, and a lower grid bias is required for optimum operation, possibly also accompanied by an increase in the optimum load resistance. The combined result is therefore to reduce the maximum power output and to reduce the grid input voltage required for full output.

It is obvious that a Class A amplifier is less affected by poor regulation in the B supply than is a Class AB1 or other amplifier drawing considerably more current at full output than at no output." (end quote)

Unfortunately a change in tube characteristics means a change in sound quality so the amplifier will not have constant tonal characteristics throughout its dynamic power range - a very important attribute.

The amplifier will be non-linear when processing normal audio signals of say 20 db dynamic range.
Importantly, this non-linear quality will apply to all power stages relying upon cathode bias, which is one reason why guitar amplifiers, which rely heavily upon accurate dynamic signal performance for their "sound" - ie transient response - prefer fixed bias.

**STC BRIMAR**, in their *Valve and Teletube Manual #8 (1959)* state:

"The source resistance of the Screen voltage supply should be kept as low as practicable, and for most applications a potential divider network, or other voltage source having good regulation, is preferred to a series resistor.

This is particularly applicable to pentodes having aligned Grids, and to unaligned Tetrodes, where the Screen current is subject to relatively wide variation with operating conditions and between individual valves. In the case of Pentodes with unaligned Grids, the variation is smaller and series resistors may be used.

Where variable Grid bias is applied to control gain, the use of a high-impedance supply to the Screen will result in a lengthening of the Grid base.

At low anode voltages the Screen current tends to increase greatly, and care is required to avoid exceeding the Screen dissipation. The Anode voltage should not be removed while the Screen is energised." (End quote)

**EIMAC**, in their *Care and Feeding of Power Tubes* website, present a different and comprehensive view of Screen-Grid current flow and express concerns regarding secondary emission in tetrodes and pentodes.

Of particular importance is the concept of reverse current flow in the Screen-Grid circuit caused by secondary emission - requiring not only a low impedance power supply for AC signal circuits but also a low resistance power supply for the reverse current flow in the DC B+ circuit.

EIMAC recommend a current-bleeding resistor in the Screen-Grid supply circuit.

However these conditions are less severe with pentodes, due to the control over secondary emission by their Suppressor-Grid (Grid 3)

Unfortunately Eimac's copyright restrictions prevent me from reproducing it here for your convenience - you will have to look it up yourself at the above referenced link.

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**6. SCREEN GRID (GRID # 2) - OPERATING VOLTAGE**

**RCA Receiving Tube Handbook RC-19** explains at Page 7:

"The Screen Grid is operated at a positive voltage and, therefore, attracts electrons from the cathode. However, because of the comparatively large space between wires of the Screen Grid, most of the electrons drawn to the Screen Grid pass through it. Hence the Screen Grid supplies an electrostatic force pulling electrons from the Cathode to the Plate. At the same time, the Screen Grid shields the electrons between Cathode and Screen Grid from the Plate so that the Plate exerts very little electrostatic force on electrons near the Cathode.

So long as the Plate voltage is higher than the Screen Grid voltage, Plate current in a Screen Grid tube depends to a great degree on the Screen Grid voltage and very little on the Plate voltage" (end quote)

**Important Notice:** **STC BRIMAR**, in their *Valve and Teletube Manual #8 (1959)* state:

"At low anode voltages the screen current tends to increase greatly, and care is required to avoid exceeding the screen dissipation." (end quote)

**RCA Transmitting Tube Handbook TT-4** at page 8 further explains:

"If the negative excursion of the output signal swings the Plate to a voltage less positive than that of the Screen-Grid, electrons moving from the Screen-Grid to the Plate tend to reverse their direction and return to the Screen-Grid.

The resulting decrease in Plate current causes a corresponding rise in Plate voltage, which terminates the negative swing of the
output signal before it completes its full excursion. This effect, which tends to reduce the power output of a tetrode below that obtainable from a triode having equivalent plate-input rating, is emphasised considerably when there is secondary emission from the Plate.

The loss of a portion of the output energy which occurs in a tetrode under these conditions reduces the power-handling capabilities of the tube, and causes serious distortion of the signal waveform.

The output of the tube, therefore, contains harmonics of the signal frequency and other spurious frequencies which may cause considerable interference to communications service. Such distortion may also be highly objectionable to the ear or to the eye when a tetrode is used as an audio or video amplifier.

Although this effect may be minimised by reducing the amplitude of the plate-voltage swing so that the plate voltage never swings negative with respect to the Screen Grid voltage, this expedient imposes further limitations on the tube output."

"Dynatron Action":

"The abrupt rise in the plate-voltage of a tetrode caused by the reversal of electron flow tends to draw both primary and secondary electrons back to the Plate. Collection of these electrons then makes the Plate less positive than the Screen Grid so that the tube current tends to reverse again.

This interchange of electrons between Plate and Screen Grid, called Dynatron Action, may continue for several cycles, and is equivalent to an oscillatory current. Although dynatron action forms the basis of certain tetrode oscillator circuits, it is highly objectionable when a tube is used solely as an amplifier." (end quote)

RCA Transmitting Tube Handbook TT-4 at page 8 further explains that the dynatron action problem is intended to be overcome by the addition of a Suppressor Grid (Grid #3) in Pentodes which, when connected to the Cathode, establishes a negative electrostatic field between the Screen Grid and Plate, to effectively prevent both primary and secondary electrons from flowing backwards to the Screen Grid.

A different and comprehensive view of secondary emission in tetrodes and pentodes is provided by Eimac at their website - Care and Feeding of Power Tubes. Unfortunately Eimac's copyright restrictions prevent me from reproducing it here for your convenience - you will have to look it up yourself.

Essentially, there is a condition whereby the electron flow between the Screen-Grid and Plate cannot be controlled by Grid 1 - ie once electrons have passed through the Screen-Grid they are more or less free to do whatever they want. Some go on to the Plate but others return to the Screen-Grid.

Under certain conditions a situation of "thermal runaway" may develop, resulting in excessive Screen-Grid dissipation and potential fusing of the Screen-Grid wire caused by excessive current flow back through the Screen-Grid to AC ground.

PENTODES AND BEAM POWER TUBES:

However, notwithstanding the above propositions, RCA Receiving Tube Manual RC-19 also states at Page 8:

"In power output pentodes, the Suppressor Grid (Grid #3) makes possible higher power output with lower grid-driving voltage; in radio-frequency amplifier pentodes the Suppressor Grid makes possible high voltage amplification at moderate values of plate voltage. These desirable features result from the fact that the plate voltage swing can be made very large. In fact, the Plate voltage may be as low, or lower than, the Screen Grid voltage without serious loss in signal gain capability."

In the case of Beam Power Tubes, RCA Receiving Tube Manual RC-19 further states at Page 8:

"When a Beam Power Tube (ie a tetrode) is designed without an actual Suppressor Grid (Grid #3), the electrodes are so spaced that secondary emission from the Plate is suppressed by space-charge effects between Screen Grid and Plate. The space-charge is produced by the slowing up of electrons travelling from a high-potential screen Grid to a lower potential Plate. In this low-velocity region, the space-charge produced is sufficient to repel secondary electrons emitted from the Plate and to cause them to return to the Plate.

A feature of the Beam Power Tube is its low Screen-Grid current. The Screen Grid and Control Grid wires are wound so that each turn of the Screen Grid is shaded from the cathode by a Control Grid turn. This alignment of the screen Grid and Control Grid causes the electrons to travel in sheets between the turns of the screen Grid so that very few of them strike the Screen Grid. Because of the effective suppressor action provided by the space-charge and because of the low current drawn by the Screen Grid, the Beam Power Tube has the advantages of high power output, high power sensitivity, and high efficiency."
Fig. 4 shows the structure of a Beam Power Tube employing space-charge suppression and illustrates how the electrons are confined to beams. The beam condition illustrated is that for a Plate potential less than the Screen Grid potential."

The design shown is typical of the 807 tube. Interestingly, the 807 (together with the 814) has the lowest Screen-Grid current of any of the popular output tubes - ie substantially more of the total electron flow reaches the Plate, resulting in a more efficient tube.

However, as will be seen below, increased Screen-Grid Voltage rating can only be achieved by increasing the physical separation distance between Grid #1 and Grid #2 in the tube - ie shifting the Screen-Grid closer to the Plate, and/or reducing the number of turns in the Screen-Grid wire to inhibit electron attraction - in such a way as to ensure compliance with the tube's published specifications - resulting in reduced control over electron flow and a change in the "sound" of the tube.

Thus a 6L6GC with its 500 VDC Screen Grid rating, will have different dynamic characteristics (linearity) and will sound different to a 6L6G with its 270 VDC Screen Grid rating - because its construction is different.

Theoretically, the earlier 6L6G tube having lower ratings should perform better than the later 6L6GC tube with higher ratings, because in the latter case, the Screen-Grid has less electronic control over electron flow in the tube.

The 6L6GC thus would reasonably be expected to demonstrate higher total distortion than the 6L6G when operated within the limits of the design ratings for the 6L6G, even though power output from both types should be the same when operated under these conditions.

For a very detailed explanation of Beam Power Tube design and construction, refer to the engineering paper BEAM POWER TUBES by RCA tube guru Otto Schade. Read with care, this paper provides the reader with an excellent insight into the design rationale and theory of Beam Power Tube design. This paper is part of a set published in RCA Electron Tubes Volume 1 (1935-1941) and Volume 2 (1942-1948).

Note: The original McIntosh amplifier applied 420 VDC to both Plates and Screen Grids, the latter being well above the rated 270 VDC design-centre value. It so happens that the much upgraded 6L6GC - and the better 7581 - are capable of handling the 420 VDC on the Screens with much less distress, so the 6L6GC and 7581 are therefore recommended as superior replacement tubes for the McIntosh. In this application, the hi-fi version of the 6L6 - the 7027A - is also suitable, however the pin connections are different and some rewiring of the socket connections may be necessary.

Further commentary on the screen-grid operating conditions of this amplifier was presented by Hugh Lockhart in 1956 - see http://www.tubebooks.org/Books/lockhart.pdf

Bruce DePalma, one of the few true Gurus of modern hi-fi amplifier design, presents an interesting and vital commentary on Screen-Grids and other related issues in his Design Paper - "Analog Audio Power Amplifier Design"

Bruce developed designs that enable both Ultra-linear and low Screen-Grid voltage technologies to be successfully integrated - eg Acrosound 6146 100 W RMS Hi-fi Amplifier.

7. SCREEN GRID (GRID #2) - OPTIMUM DC OPERATING VOLTAGE

To extend tube life and minimise distortion, it is recommended that the Screen Grid Voltage be as low as practicable - refer to
The following JETEC USA design specifications explicitly limit Screen-grid voltage to pre-determined criteria.

**RECEIVING TUBE SCREEN VOLTAGE RATINGS**

The voltage for the screen of a tube may be obtained from either a fixed source or through a screen dropping resistor. A voltage source is considered “fixed” if the regulation is such that no significant change in voltage takes place with variations in current.

The tube data sheets may show a maximum screen voltage, or a maximum screen supply voltage. When a maximum screen voltage is shown, the voltage measured at the screen terminal should not exceed such value under any circuit operating condition. When a maximum screen supply voltage is shown the screen voltage may be permitted to reach the rated supply voltage provided that the screen dissipation (screen current in amperes multiplied by the voltage appearing directly at the screen terminal) is held within certain specified values as indicated in Chart A.

**CHART A**
The chart represents the maximum permissible screen dissipation (as a percent of the maximum screen dissipation rating) at any screen voltage operating point. The chart shows that full rated screen dissipation is permissible up to 50% of the maximum rated screen supply voltage. From the 50% point to the full value of rated supply voltage the decrease in the allowable screen dissipation follows a curve of the parabolic form. The chart is of universal use for cases where either a fixed screen voltage or a series screen dropping resistor is used.

In the case where fixed screen applied voltage is desired it is necessary only to determine that the screen dissipation is within the boundary of the chart at the screen voltage to be used. In the case where a screen voltage dropping resistor is to be used it is necessary to determine the resistor value such that the dissipation in the screen grid is again within the same boundary of the chart. It is to be noted that the minimum value of the voltage dropping resistor is given by the factor.

$$\frac{E_{cc2}^2}{4P_{g2}}$$

where $E_{cc2}$ is the selected screen supply voltage and $P_{g2}$ is the maximum screen dissipation rating for the type.

To illustrate the use of the chart, let it be assumed that the tube data for a type stipulate ratings of 300 volts maximum screen supply voltage, and 1.0 watt maximum screen dissipation. If it is desired to operate the tube at 200 volts (66.67% of the maximum screen supply voltage rating) applied directly to the screen, the maximum allowable screen dissipation at this point (refer to Chart A) is 88% of the maximum screen dissipation, or 0.88 watt.

On the other hand, if it is desired to operate the same tube with a screen dropping resistor, the maximum screen voltage must not exceed the 300 volt rating, and the dropping resistor must be selected to hold the dissipation within the safe ratings. To assure that the tube will operate within the rating curve the dropping resistor can be de-
JETEC Specifications for Screen-Grid Operating Voltages

Notwithstanding the above JETEC design specifications - determined from extensive practical and theoretical research, design type tested performance criteria and endorsed by leading manufacturers' - numerous examples of commercial Guitar amplifiers and Public Address (PA) amplifiers demonstrate typical design with a common Plate and Screen supply (as a cost saving measure) having B+ supply voltages well above the above specified maxima. However this operating configuration does not promote either long tube life or high-fi standard performance - in fact some tube guitar amp designers deliberately configure the output stage to ensure desired distortion characteristics under sustained overload conditions. But it can also be a recipe for overheating, unreliability, short tube life, instability, parasitic oscillations and/or dynatron action in the output stage because the output tubes are running with the Plate Voltage less than the Screen Grid Voltage (because of DC voltage drop in the primary of the output transformer).

This is particularly true of low-cost output transformers having high DC resistance windings - not to mention low primary inductance and high leakage inductance which also facilitate parasitics.

Inaudible HF oscillations at full power output can easily damage loudspeakers - particularly tweeters having a "system power" or "music power" rating. RC filters across the primary windings are typically used by commercial designers to roll-off HF response in the output stage.

Remember, the purpose of the Screen-Grid is to accelerate and focus electrons towards the Plate. Excessive Screen-Grid voltage attracts excessive electrons, increasing Screen-Grid temperature, current draw, and temperature rise - yes it does matter!!

An important clue to Screen-Grid behaviour is found in the Tube Data Sheets for RF Transmitting power tubes. Here it will be seen it is common - for a particular tube type - that the Screen-Grid voltage is expressed at a constant value, irrespective of Plate voltage. Screen Grid voltage is always specified at a level substantially less than the Plate voltage.

What this practice suggests is that for a particular tube type, there will be an optimum value of Screen-Grid voltage that will be sufficiently high to attract and accelerate electrons towards the Plate - irrespective of Plate voltage - beyond which no significant advantage is gained.

The following examples illustrate this principle. Consider this sample of well known beam power tubes suitable for both RF and AF applications:

- Type 4-65A.
The recommended Screen Grid operating voltage is only 250 VDC for all Plate voltages between 600 and 2500 VDC.

- **Type 4-250A.**

  The recommended Screen Grid operating voltage is only 300 VDC for all Plate voltages between 1500 and 3000 VDC.

- **Type 4X500A.**

  The recommended Screen Grid operating voltage is only 500 VDC for all Plate voltages between 2500 and 5000 VDC.

- **Type 807.**

  The recommended Screen Grid operating voltage is only 300 VDC for all Plate voltages between 400 and 750 VDC.

Furthermore, this engineering practice suggests that because the physical distance from the Cathode (or Filament) to the Screen Grid is fixed during manufacture, once adequate Screen Grid voltage is applied to do the job then no further significant benefit will be gained by increasing the Screen Grid voltage.

This statement needs to be considered alongside the reality that if Screen Grid voltage is increased then Plate current will increase disproportionately, requiring a corresponding increase in Control Grid (Grid #1) voltage (ie more negative) to compensate and keep plate dissipation within acceptable limits - thus reducing gain and operating capability to fully drive the tube to maximum prospective power output for the available DC supply voltage.

Excessive Screen Grid voltage reduces its capacity to control electron flow in the tube and therefore affects gain, power output linearity between zero and maximum signal, and increases distortion.

Another way of expressing this is to say that as far as the Cathode is concerned, the Screen Grid is the Anode. The rate of electron flow will therefore be controlled by the Anode (Screen-Grid) voltage. What happens to the electrons after they pass through the Screen-Grid and continue their journey to the Plate is of no concern to the Cathode.

It follows that the critical design element for a Tetrode, Pentode or Beam Power Tube is the Screen-Grid voltage, because this is the effective Anode voltage.

As a rule of thumb, the screen grid supply voltage should NEVER be more than the manufacturer's rating. Higher applied Screen-Grid voltage is likely to cause self-oscillation, parasitic oscillation, dynatron action or thermal runaway - any of which can easily destroy a tube and associated components. MINIMAL Screen-Grid voltage will provide better performance including cleaner, crisper sound with less distortion.

Tube Data handbooks typically recommend Screen Grid operating voltages at only half, or even less than half, the rated maximum for a given tube type, warning us of the great control the Screen Grid has in determining tube performance.

In the case of pentodes having a separate Suppressor Grid, it is also relevant that the Suppressor Grid is usually either connected directly to the Cathode inside the tube itself, or externally wired to the Cathode. Because the Suppressor Grid is thereby at Cathode potential, it follows that excessive Screen-Grid voltage is likely to cause difficulties through interaction with the Suppressor Grid.

It is also of importance to recall that the Screen-Grids of miniature amplifying tetrodes and pentodes as used in RF stages of a receiver, or pre-amplifier stages of an audio amplifier, generally draw just a few milliamperes. Consequently, the actual Screen current compared with the diameter of the Screen-Grid wire (hence its design-centre current rating) provides an inherent safety margin of headroom in terms of Screen-Grid current rating of the wire.

This design attribute enables the Screen-Grid to be bypassed directly to ground (Cathode), effectively creating an AC short-circuit across the tube, with no apparent detrimental effect upon the Screen-Grid wire. One reason for this is the usually very high value of Screen-Grid supply resistor - often 0.5 MegOhm or more - which limits Screen-Current to safe values. However the same cannot be said for power tubes and further comments are made below on this subject.

### Plate and Screen Dissipation of Tetrodes and Pentodes

The following rare graph, courtesy of ITT-Standard publication MSE/123 published in 1963, illustrates how Screen-Grid current changes with applied DC voltage to either Screen-Grid or Control Grid.

It clearly shows at 1 kV typical Plate Voltage and 0 VDC Control-Grid Voltage, that when we increase Screen-Grid Voltage (above a critical value), the Screen-Grid current, and therefore Screen Dissipation, may increase dramatically.
Regrettably, corresponding data is not available for more negative Control-Grid voltages typical to audio applications.

![Graph showing Screen Grid Current versus Screen Grid Voltage (Vg=1000V)](image)

**ITT-Standard Type 4X150A Beam Power Tetrode**

*Radiotronics* Magazine No. 80 of October 1937 says:

"The power dissipated in the Screen circuit is added to the power in the Plate to obtain the total B supply input power. With full signal input, the power delivered to the Plate circuit is the product of the full signal Plate supply voltage and the full-signal DC Plate current. The power dissipated by the Plate in heat is the difference between the power supplied to the Plate circuit and the power supplied to the load.

Screen dissipation increases with load resistance. In order to visualise this relation, assume that the sum of the Screen and Plate current is independent of Plate voltage for zero Control Grid bias, or for a negative value of it. A decrease in Plate voltage causes a certain decrease in Plate current; *it is assumed that the Screen Current rises by an equal amount*. Hence, when the Screen Grid valve operates with a load which intersects the zero-bias characteristics below the knee, the Screen current rises to high values during low-Plate voltage excursions of the output voltage. This action produces a rise in the DC value of Screen current with signal. Therefore, the Screen dissipation with full signal input may be several times the zero-signal value. To reduce Screen dissipation, the load should always be chosen so that it passes through the knee of the zero-bias characteristic.

Increasing the applied signal voltage to a value higher than that for which the load is designed also increases Screen dissipation. For this reason, it may be advisable to use a value of load which is slightly less than the optimum value. This precaution has another advantage, which is especially important at high audio frequencies. The impedance of a loudspeaker increases with frequency. When the load is adjusted for the proper value at 400 Hz, the load is usually too high at 2000 Hz; thus a Screen dissipation limit may be exceeded at 2000 Hz even though operation is normal at 400 Hz. The use of a load which passes through the zero bias characteristic somewhat above the knee is desirable for these reasons." (end quote)

Note: The conditions described above are very likely in lead guitar amplifiers where the signal is of a single frequency nature.

**METHOD 1: AN EMPIRICAL OPTIMISING APPROACH:**

The physical spacing between the cathode and anode in a vacuum tube is the gap across which the electrons must travel, and is the gap across which applied voltage is measured and present (Plate Voltage).

Hence it can be stated with certainty that the **DC voltage gradient across the cathode to anode gap is essentially linear**.

Note: For those technically competent, early texts (Spangenberg, Beck, Argimbeau, Chaffee, Reicht, etc.) clearly show this voltage tensor as having an exponential-shape, albeit not strongly, which starts at zero, then goes negative, then goes positive to cross through zero at the "virtual cathode" point, and then climbs (always lagging the linear DC voltage gradient) toward the
maximum applied DC voltage. (Thanks to Earles L. Mc Caul for this contribution)

A simple example of this is seen in a vacuum tube rectifier, which comprises only a Cathode and an Anode - with a vacuum gap between them.

It is relevant to note that a triode tube is just a rectifier with a Control Grid inserted between the Cathode and Anode to regulate the electron flow through the tube - and hence through the circuit.

Examination of the physical construction of a vacuum tube, demonstrates that the control grids (Grid #1, Grid #2 and Grid #3 etc) are fixed in precise physical relationship to each other, to the anode, and to the cathode.

Further examination reveals that the relationship between manufacturers’ Rated Plate Voltage and Rated Screen Grid Voltage is directly proportional to the physical distance between each of them and to their common Cathode.

Given that the Rated Screen Grid Voltage is a maximum value and directly physically correlates with Rated Plate Voltage, which is also a maximum value, it follows that when the actual applied Plate Voltage is less than the Rated Maximum - to maintain linearity, or equal distribution of the applied DC voltage gradient across the tube, the applied Screen Grid Voltage MUST be directly proportional to the linear relationship between Cathode to Screen Grid, and Screen Grid to Anode, within the tube.

If the Screen Grid Voltage exceeds the value indicated from the above method - as is common design practice - it can be predicted with certainty that the velocity of electrons between Cathode and Screen Grid will increase, resulting in increased Screen Grid Current, more secondary electrons produced from the Plate, increased distortion and greater propensity for the tube to oscillate.

More importantly, there will be a mismatch between the "natural" Screen Grid Voltage - derived from the voltage gradient created by its physical relationship in the electron stream gap - and the applied Screen Grid Voltage.

Thus this approach is suggested to determine the preferred Screen Grid voltage.

It assumes a linear relationship between Plate and Screen Grid voltages, by the formula:

\[
\text{optimum screen grid voltage} = \frac{\text{actual plate voltage}}{\text{maximum rated plate voltage}} \times \frac{\text{maximum rated screen grid voltage}}{\text{maximum rated plate voltage}}
\]

Of course, plate and screen voltages are measured to the cathode or filament, as applicable.

This design approach ensures the Screen Grid voltage is optimised and will avoid unwanted secondary emissions and over-excitation of the tube.

Note: Where the applied Plate Voltage exceeds the Rated Plate Voltage - such as in guitar amplifiers - it would seem prudent to also proportionately increase the applied Screen Grid Voltage to maintain voltage gradient equilibrium. Note however there are risks with this form of tube abuse and premature failure is a likely outcome.

METHOD 2: A LOGICAL APPROACH:

RCA Receiving Tube Handbook RC-19 states at Page 8:

"In the case of Screen-Grid tubes, the proximity of the positive Screen-Grid to the Plate offers a strong attraction to secondary electrons, and particularly so if the Plate voltage swings lower than the Screen-Grid voltage. This effect lowers the Plate current and limits the useful Plate voltage swing for Tetrodes." (end quote)

Thus, another method is to adopt a policy that to optimise performance whilst maximising tube life, the Screen-Grid voltage must never exceed the Plate voltage at full negative swing signal.

This is to ensure that the Plate will never swing negative in relation to the Screen-Grid thus causing the Screen to replace the Plate as the PRIMARY ANODE during that portion of the signal cycle where the Plate is more negative than the Screen Grid.

In other words, it is essential that the primary electron stream continue on past the Screen-grid to be collected at the Plate - otherwise the Screen-grid will conduct too much current and melt.

Note also that the Screen-Grids are normally connected to AC earth via the screen bypass capacitor. Thus if the Screen-Grids become the primary anode the signal will be short-circuited to ground, with disastrous consequences for distortion, linearity and tube life (very short).

Therefore, returning to the primary proposition of this article - ie that Screen-Grid DC voltage must always be less than its Plate
voltage, an approximate value for optimising the DC Screen-Grid voltage may be determined by calculating the maximum Plate to Plate AC signal voltage across the full output transformer primary winding.

This approximation, ignoring the effects of power factor in the AC circuit, may be determined by calculating the square root of the value resultant from multiplying the output power in watts RMS by the primary load impedance. \( \text{rms watts} = \frac{\text{output voltage squared}}{\text{load resistance}} \)

eg Power output is 100 W RMS from a primary load impedance of 5,000 ohms.

Step 1: \( 100 \times 5000 = 500,000 \).
Step 2: Determine the square root of 500,000 = 707.
Thus AC signal voltage is 707 V RMS plate to plate.
Step 3: Half of that is 354 Volts. (half swings positive, half swings negative)
Step 4: Hence to determine maximum permissible safe Screen Grid DC voltage subtract 354 from the actual Plate to Cathode/Filament voltage.

For example, if the Plate voltage is 600 VDC subtract 354 V AC = 246 VDC absolute maximum applied to the Screen-Grids.

Obviously a lower voltage is desirable to ensure the electron flow continues past the Screen-Grid and on to the Plate, which is their intended destination.

Remember too, that this calculation is based upon the tube manufacturer’s rated output power - ie not actual, which may be more if:

- a) the grid bias (Grid #1) is not set accurately, or
- b) the tubes have higher conductance than specified, or
- c) the amplifier is driven into overload, or
- d) a very high amplitude transient signal is amplified, or
- e) a different load impedance is used than that recommended by the manufacturer, or
- f) the reflected load impedance is different to the theoretical due to a variance between the stated and the actual loudspeaker impedance, or
- g) the signal frequency coincides with the loudspeaker resonance frequency (primary load may increase up to six times the nominal value). This situation is very likely with single note instruments such as an electronic organ or bass guitar, where no signal averaging occurs.

To be sure, a margin of say 10% might reasonably be applied, so the calculated DC Screen-Grid voltage should be reduced by at least a further 10% - more to accommodate transients.

It is interesting to note also that although RCA state in Transmitting Tube Manual TT-4 at page 9: “Beam Power Tubes may also employ Suppressor Grids rather than space-charge effects to prevent the reversal of electron flow when the Plate swings negative with respect to the Screen Grid.” - a study of tube specifications reveals that RF Beam Power Tubes always have a rated Screen Grid voltage substantially lower than the rated Plate voltage, thereby rendering the foregoing statement by RCA as somewhat theoretical for both Pentodes and Beam Power Tubes.

It will be seen that when the above suggested formula is used to determine the negative AC signal voltage swing the resultant calculated Screen Grid DC voltage will usually be above the manufacturer’s Screen Grid DC Voltage Rating.

Using this method it will be observed that when the tube manufacturer’s maximum rated Screen Grid DC voltage is used, the AC signal voltage during its negative swing will still always be above the Screen Grid DC voltage, thus preventing adverse effects.

eg compare these tubes of similar 125W rating:

<table>
<thead>
<tr>
<th>Type</th>
<th>Construction</th>
<th>Max Screen DC Volts</th>
<th>Max. Plate DC Volts</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-125A</td>
<td>Beam Power Tetrode</td>
<td>400</td>
<td>3,000</td>
</tr>
<tr>
<td>4E27A/5-125B</td>
<td>Beam Power Pentode</td>
<td>750</td>
<td>4,000</td>
</tr>
<tr>
<td>803</td>
<td>Pentode</td>
<td>600</td>
<td>2,000</td>
</tr>
<tr>
<td>813</td>
<td>Beam Power Pentode</td>
<td>1,100</td>
<td>2,250</td>
</tr>
</tbody>
</table>

IMPORTANT NOTE:

All the above discussion assumes the signal voltage at the Screen Grid to be simple sine wave waveform - of course in practice it is not. This gives us yet another reason to further reduce Grid #2 voltage to ensure it always remains negative to the Plate.
8. RESISTANCE IN THE GRID #2 SUPPLY - GRID STOPPER RESISTORS AND SCREEN GRID SUPPLY DROPPING RESISTOR

RCA Transmitting Tube Handbook RC-19 states at page 60:

"The positive voltage for the Screen Grid (Grid #2) of Screen-Grid tubes may be obtained from a tap on a voltage divider, from a potentiometer, or from a series resistor connected to a high-voltage source, depending on the particular type of tube and its application. The Screen-Grid voltage for Tetrodes should be obtained from a voltage divider or a potentiometer, rather than through a series resistor from a high-voltage source because of the characteristic Screen-Grid current variations of Tetrodes.

When Pentodes or Beam Power Tubes are operated under conditions where a large shift of Plate and Screen-Grid currents does not take place with the application of the signal, the Screen-Grid voltage may be obtained through a series resistor from a high-voltage source. This method of supply is possible because of the high uniformity of the Screen-Grid current characteristics in Pentodes and Beam Power Tubes. Because the Screen-Grid voltage rises with increase in bias and resulting decrease in Screen-Grid current, the cut-off characteristic of a Pentode is extended by this method of supply.

This method is sometimes used to increase the range of signals which can be handled by a Pentode. When used in resistance-coupled amplifier circuits employing Pentodes in combination with the cathode-biasing method, it minimises the need for circuit adjustments.

When power Pentodes and Beam Power Tubes are operated under conditions such that there is a large change in Plate and Screen-Grid currents with the application of signal, the series resistor method of obtaining Screen-Grid voltage should not be used. A change in Screen-Grid current appears as a change in the voltage drop across the series resistor in the Screen-Grid circuit; the result is a change in the power output and an increase in distortion. The Screen-Grid voltage should be obtained from a point in the Plate voltage supply filter system having the correct voltage, or from a separate source.

It is important to note that the Plate voltage of Tetrodes, Pentodes and Beam Power Tubes should be applied before or simultaneously with the Screen-Grid voltage. Otherwise, with voltage on the Screen-Grid only, the Screen-Grid current may rise high enough to cause excessive Screen-Grid dissipation." (end quote)

RCA Transmitting Tube Handbook TT-4 also states at p62:

"The danger of excessive screen-grid voltages is present principally when screen-grid voltage is obtained from the plate supply through a series dropping resistor. In this type of supply circuit, sufficient resistance is connected between the screen-grid and the plate supply to assure that the screen-grid voltage and dissipation at the values of screen-grid current, bias and driving voltage required for full output are within the maximum ratings for the tube. Any condition which reduces the current through the screen-grid dropping resistor to a very low value, therefore, may cause the screen-grid voltage to rise to an excessive value." (end quote)

These sentiments are also expressed by Philips and STC Brimar.

It is therefore preferable that the dropping resistor should be part of a voltage divider network to further stabilise the supply and to provide a direct current circuit to ground. All resistors in the voltage divider must be suitably rated.

When a dropping resistor is used from the B+ supply, a suitably large (ie large enough to offer a low-impedance path for the frequency range being amplified) bypass electrolytic capacitor is essential to provide a return circuit to bypass AC signal voltage to ground. Note also that the power losses in such a resistor can be high, so a suitably rated wire-wound resistor is essential to cope with the heat losses - eg typically 10 to 20W continuous power dissipation rating. Note also that this resistor may become very hot after a while, so it must be located away from heat sensitive components such as electrolytic capacitors. The higher the resistor's power dissipation rating the lower will be its temperature rise (Noting that present-day IEC standards permit a substantially higher temperature rise than in days of old). A useful approach is to halve the resistor manufacturer's rated dissipation.

In all cases, non-inductive grid stopper resistors (eg 500 to 1,000 ohms) must be fitted as close as is practicable to the socket pin (read VERY close) to provide stable operation, minimise RF signal pickup, minimise inductance in the wiring, and prevent
parasitic-oscillation in the tube. Note that carbon film resistors may self-ignite if the insulating coating is not of fire retardant material - be warned!! Composition carbon resistors may be a better practicable choice.

Philips Miniwatt put it this way in their "Miniwatt Electronics Handbook" (Australia 1960):

"The maximum value of peak Grid #2 dissipation is given to avoid the risk of impairing valve life by overheating the Grid #2 during long periods of excitation, which sometimes occurs with music or speech. In most cases, insertion of a non-decoupled series resistor of 500 to 1000 ohms in the Grid #2 lead will reduce the actual value of peak dissipation to a large extent and not seriously affect the output power.

During normal excitation with music or speech there will in general be no danger of exceeding the maximum value of Grid #2 dissipation when the valve is operated according to the published operating conditions.

In applications with a sustained sine wave input voltage" (bass guitar and electronic organ amplifier builders please note) "there is a great risk of exceeding the maximum value of Grid #2 dissipation, so that in general full excitation is not allowed.

In order to prevent the maximum permissible Grid #2 dissipation from being exceeded it is necessary to ensure that the Plate is always correctly loaded.

Hence the Plate lead must not be disconnected, nor must the loudspeaker be switched out, without replacing it by an equivalent resistor". (end quote)

In the case of tetrode and pentode operation, do not use excessive values of unbypassed (non-decoupled) Screen series resistance, because DC supply to the screen grid is likely to fluctuate substantially with screen current - thereby introducing non-linearity, as well as separating the screen from direct connection to AC ground.

Voltage drop from DC Screen Current is a particular challenge with parallel-push-pull operation. Care is also needed with conventional Class AB or Class B operation of single paired tubes.

Notwithstanding that though a word of caution:

Philips Miniwatt warn us in this way in their "Miniwatt Electronics Handbook" (1960):

"If the circuit is designed for operation of the valve below the knee of its plate current plate voltage characteristics, the Grid #2 series resistor must have a minimum value of * ohms in order to avoid the occurrence of Barkhausen oscillations." (end quote)

Some Food for Thought:

The usually recommended value of Grid Stopper Resistor is around 100 to 500 ohms (although to save on cost many commercial amps successfully connect directly, with no Grid Stopper at all).

This has been standard practice for more than 60 years.

Interestingly, all the early tube literature shows the Screen Grid connected directly to the B battery, with no bypass capacitor. This tells us that conceptually, early designers regarded the Screen Grid as being at a DC potential, with either no regard for the AC signal component, or a reality that the battery provided the necessary AC bypass return circuit path to earth.

However an empirical approach derived from the manufacturers' data described on my ultra-linear operation page suggests a value of around at least one half the Plate to Plate load impedance presented by the output transformer.

The basis for this proposition is that in normal push-pull tetrode or pentode operation there is little or no resistance between Grid #2 and the B+ supply, so therefore there will be no Screen to Screen load equating to the Plate to Plate load.

This is because the centre-tap of the output transformer primary is connected to AC earth (ground) via the bypass/filter cap at that point.

In other words, in the case of normal push-pull tetrode or pentode operation there will be an AC SHORT-CIRCUIT between the Screen Grids - and between the Screen-grids and their respective Cathodes.

Although this "short-circuit" - ie no load operation - will obviously increase Screen current, the AC signal current in the Screen Grids will not appear in the output because it is diverted to earth through the bypass capacitor.

However no-load operation of the Screen Grids will increase the number of electrons collected by the Screens - a phenomena we do not want - because we want the electrons to be only attracted to, but then continue on through and past the Screen Grids on their way to their respective Plates.
Thus electrons collected by the Screen Grids not only increase Screen Current, but also divert electrons from the Plates and therefore reduce power output.

It is this effect that results in the standard rating of "Screen Dissipation" - expressed in Watts. "Screen Dissipation" is the result of DC Screen Input Watts minus AC Screen Grid Signal Output Watts. Thus if AC Signal Output Watts is zero or close to zero, because the AC output between push-pull Screen Grids is more or less short-circuited, then the DC Input Watts will be maximised under all signal conditions.

What we want is for the Screen Grids to be at a DC potential sufficiently high enough to attract and accelerate electrons towards the Plates but, to maximise power output, not to collect and divert them to earth through the B+ supply.

Clearly there will be a particular value of Screen Grid Stopper Resistor that will provide optimum balance between the conventional "short-circuited" Screen Grid configuration and an arrangement whereby the Screen Grids are suitably loaded.

The optimum value will clearly be variable depending upon the particular circuit configuration and operating voltages.

However, as a rule of thumb, and noting the advice of Philips Miniwatt to instal a value of Grid #2 resistor of between 500 to 1000 ohms in each Grid #2 supply lead, we can assume that a value of 50% of the Plate to Plate primary load impedance is an approximate ideal for the Screen to Screen loading.

This will result in a grid stopper resistor value of:

500 ohms per Screen Grid when the transformer primary load impedance is 2,000 ohms Plate to Plate
1000 ohms per Screen Grid when the primary transformer primary load impedance is 4,000 ohms Plate to Plate
2000 ohms per Screen Grid when the primary transformer primary load impedance is 8,000 ohms Plate to Plate

For other values of Plate to Plate load, calculate on the basis that each Screen Grid resistor should be 25% of the transformer Plate to Plate primary load impedance.

In all cases, pursuant to Philips Miniwatt advice, the Screen Grid resistor is "non-decoupled" - ie is unbypassed.

This resistor must be installed directly to the Grid #2 pin of the tube socket and be preferably non-inductive.

The Screen resistors must have sufficient heat rating to operate safely and reliably without distress.

When multiple pairs of output tubes are used in parallel push-pull configurations, the Screen currents can attain reasonably high values - eg 4 x 6CA7/EL34 = 100 mA. Ensure the Screen Grid resistors can handle this current without excessive heating, noting the resistors will conduct heat from the tube pin/socket in addition to internal heat losses and temperature rise.

In multiple tube operation, to accommodate variations between individual tubes and to minimise the risk of self-oscillation, each Screen-Grid must be supplied from its own individual grid-stopper resistor. This method also enables each grid-stopper resistor to be mounted directly to each individual tube socket.

9. "ULTRA-LINEAR" OPERATION

An alternative to normal tetrode, pentode or beam power tube configurations is the ultra-linear circuit, that avoids the need for a separate screen grid supply.

"ULTRA-LINEAR" is a term, when applied to audio amplifiers, that describes the output stage configuration whereby the screen grids (Grid 2) of tetrodes or pentodes are fed from a tapping on the primary of the output transformer, instead of from a separate DC supply.

Ultra-linear is also known as distributed load operation.

Taking note of the above information regarding Screen-Grids, full details are provided in my separate ULTRA-LINEAR page.

10. GUITAR AMPLIFIERS

Using the above knowledge about the behaviour of Screen-Grids, the following design rules can be applied to guitar amplifiers:
a) **BRIGHT, CLEAN SOUND** (Minimum Distortion) - eg Lead Guitar, Country, Steel

- Screen-Grids to be supplied from a reasonably constant voltage power supply. In simplest form this can be just a large filter cap - say 100 uF after a filter choke (not a dropping resistor) from the Plate supply
- Silicon Rectifier - full-wave bridge or voltage doubler
- Plates to be supplied from a transient-current capable power supply. Use high-quality industrial grade (high-ripple) large filter caps to plate supply - at least 100 uF per each pair of output tubes (double that for bass guitar amps)
- Power Transformer continuous current rating to be double the theoretical output stage Cathode current (to improve regulation)
- Screen-Grids preferably supplied from a separate low-voltage (ie 40% of Plate Voltage) supply. Where Plates and Screen-Grids are supplied from a common pwer supply then the filter caps should be as large as will fit into the chassis - preferably 200 uF minimum - the bigger the better!!
- Tube heaters preferably supplied from a separate transformer (to prevent voltage drop during peak power output)
- Beam power tubes. Tubes must have aligned Screen-Grids (eg 6V6GT, 5881 (USA), 6L6GC/7027, 6550, KT66, KT88)
- Output Transformer must have low DC resistance (to prevent voltage drop on peak power signals)
- Output Transformer for lead-guitar amps to have low inductance (to rolloff low frequencies and prevent overloading of the loudspeaker - especially in an open-backed cabinet)
- ALL interstage coupling capacitors selected to provide -3db rolloff at 50 Hz
- No negative feedback loop from loudspeaker
- Grid #1 (control Grid) supplied from a full-wave rectifier
- Grid #1 stopper resistors to be as low a value as is practicable - eg 100 k Ohms max per tube
- Class AB2 or Class B operation

b) **SMOOTH, NATURAL SOUND** - eg Jazz, Rythm, Folk, Bass

- All the above but larger interstage coupling capacitors
- Ultra-linear output stage and parallel-push-pull tubes configuration is essential for bass guitar (to reduce output impedance)
- Highest practicable loudspeaker impedance - eg series connected multiple loudpeakers (to reduce Output Transformer turns ratio)
- Silicon Rectifier - full-wave, full-wave bridge or voltage doubler.
- Indirectly heated tube rectifier - eg 5AR4, 5V4G, 5Z4 etc - can be used but good filtering and regulation is needed (Not recommended for bass)
- Class AB1 or AB2 operation

c) **DISTORTED SOUND** - eg Grunge, Heavy Metal, Blues

- Directly heated tube rectifier (to ensure high voltage drop on transient peaks) - eg 5AS4, 5U4G/GB, 5Y3GT, 5Z3 etc
- Small filter caps - eg 8 or 16 uF (to provide poor regulation)
- High DC resistance filter choke (to provide voltage drop on transient peaks)
- Plates and Screen-Grids supplied from common power supply
- Plates and Screen-Grids at the same DC voltage
Output Transformer to have high DC resistance (to reduce Plate voltage on transient peaks)

- Pentode output tubes - eg EL34, EL84
- Cathode bias
- Class A operation

**BASS GUITAR**

- Screen-Grids to be supplied from a reasonably constant voltage power supply. In simplest form this can be just a large filter cap - say 100 uF after a filter choke (not a dropping resistor) from the Plate supply
- Silicon Rectifier - full-wave bridge or voltage doubler
- Plates to be supplied from a transient-current capable power supply. Use high-quality industrial grade (high-ripple) large filter caps to plate supply - at least 100 uF per each pair of output tubes (double that for bass guitar amps)
- Power Transformer continuous current rating to be double the theoretical output stage Cathode current (to improve regulation)
- Screen-Grids preferably supplied from a separate low-voltage (ie 40% of Plate Voltage) supply. Where Plates and Screen-Grids are supplied from a common power supply then the filter caps should be as large as will fit into the chassis - preferably 200 uF minimum per pair of tubes - the bigger the better!!
- Tube heaters preferably supplied from a separate transformer (to prevent voltage drop during peak power output)
- Beam power tubes. Tubes must have aligned Screen-Grids (eg 6V6GT, 5881 (USA), 6L6GC/7027, 6550, KT66, KT88)
- Output Transformer must have low DC resistance (to prevent voltage drop on peak power signals)
- Output Transformer for bass guitar amps to have grain-oriented silicon steel laminations and high inductance (to ensure high power at low frequencies). Preferably interleaved windings for good frequency response, stability and low leakage capacitance.
- All interstage coupling capacitors selected to provide -3db rolloff at 20 Hz
- No negative feedback loop from loudspeaker
- Grid #1 (Control Grid) supplied from a full-wave rectifier - preferably from a separate transformer
- Grid #1 stopper resistors to be as low a value as is practicable - eg 100 k Ohms max per tube
- Class AB2 or Class B operation

Please let me know if you can add to this body of new knowledge and I will add it to this commentary.

Of course the smart thing to do here is to use tubes that are already triodes - instead of messing about with compromises - but then none of the triodes are beam tubes and thus do not offer the benefits of beam tube technology.

Also most of us have a junkbox stock of perfectly good tetrodes, pentodes or beam power tubes just waiting to be used - so it is a tough call.
ULTRA-LINEAR OPERATION, also known as DISTRIBUTED LOAD OPERATION, is a term when applied to single-ended or push-pull vacuum tube audio amplifiers, that describes the particular output stage configuration whereby the Screen Grids (Grid 2) of Tetrodes, Pentodes or Beam Power Tubes are fed from a tapping in the output transformer (single-ended) or each half of the primary of the output transformer (push-pull) - typically 43% turns or 18.5% impedance when measured from the centre-tap, instead of from a DC supply either independent of, or common to, the anodes.

The sonic properties of the ultra-linear output stage configuration - albeit single-ended or push-pull design - are midway between triode and tetrode/beam power tube "tone".

Some audio-engineers describe the sound of triodes as "smooth, sweet, mellow, natural" and tetrode/beam power tubes as "clean, bright, sharp, punchy".

Technically speaking, the ultra-linear configuration delivers the same power output as for pentode operation of the same tube under the same operating conditions and typically about twice the power output of triode operation of the same tube under the same operating conditions with the same applied DC voltages - but with substantially less harmonic distortion or intermodulation distortion (see comparative performance graph below).

The ultra-linear configuration also offers improved overload characteristics, resulting in more effective power output - ie what the listener actually hears at full power levels.

Output impedance is similar to triodes, allowing minimal or zero negative loop feedback to be used.

The ultra-linear amplifier concept is beautifully described by David Hafler and Herbert Keroes in their 1952 US Patent Application 2710312.

The following extract is included for convenience:
ULTRA LINEAR AMPLIFIERS

David Hafler and Herbert I. Keroes, Philadelphia, Pa., assignors to Acro Products Company, Philadelphia, Pa., a firm

Application May 20, 1952, Serial No. 288,908

6 Claims. (Cl. 179—171)

The present invention relates generally to amplifiers, and more particularly to amplifiers capable of wide band linear response, operable with substantially no distortion produced by harmonic response or intermodulation over a wide dynamic range, and with excellent efficiency. The amplifier of our invention finds particular application to audio power amplifiers, but may be applied with equal effect to a wide range of uses, and at supersonic and radio frequencies, as well as at audio frequencies.

It can be demonstrated that a wide pass band and low harmonic response, in an audio power amplifier, do not of themselves provide quality performance, when performance is judged by the initiated listener, because speech and music are not of static nature. There have, accordingly, been developed criteria of amplifier performance in terms of intermodulation distortion analysis and square wave testing, both of which simulate dynamic conditions to considerable extent. Even such tests are not fully determinative of amplifier performance, since amplifiers which test well do not always sound well, although amplifiers which test poorly always sound poorly.

On the basis of listening tests, which are conceded to provide the ultimate criteria, there are two schools of thought. One adheres to the use of triode amplifiers, on the ground that such amplifiers produce sweet or smooth sound. The other adheres to the use of tetrodes, usually of the beam power type, as providing crisp or clean sound. Each tube type obviously produces its
own character of distortion, which is pleasing to its advocates, and displeasing to its opponents. It is found that these distortions are elusive, and unmeasurable, but nevertheless real to the critical listener.

It would then appear that reconciliation of the two schools of thought could only be accomplished by some new tube type, not presently available, and which might provide a response acceptable to both. Such a tube should have certain desirable electrical characteristics, in addition, which are not presently all available in either the triode or the tetrode. These may be listed as follows:

(1) Low internal impedance—now offered by the triode but not the tetrode.

(2) High power sensitivity—now offered by the tetrode but not the triode.

(3) Lower harmonic and intermodulation distortion than either the triode or the tetrode, at both high and low levels.

(4) High efficiency, to permit adequate power output without undue bulk or cost.

The basic difference between the triode and the tetrode is the screen grid in the latter. Its presence gives the tetrode high efficiency, but its absence gives the triode low plate resistance.

When the screen grid of a tetrode is connected directly to the anode of the tetrode the resulting tube is effectively a triode, which, however, has limited power output and dissipation. We have therefore analyzed the effects of tetrode operation in intermediate conditions, i.e. with the screen connected to part of the load as an active tube output element. In this condition the screen is partially energized by the output signal due to plate current variations, and partially by a D.C. static operating potential. The distinction from full triode operation of a screen grid tube is then, that the screen is not connected directly to the anode, but across
part of the anode load only.

Experimentation on this basis has produced remarkable and unexpected results. It is found that for specific ranges of percentage of screen loading taken in comparison with anode loading, depending on tube types employed and modes of operation, very favorable operational characteristics result. In this connection a tetrode, operated in the normal manner, is taken to have 0% screen loading. When operated as a full triode it is taken to have 100% screen loading. For intermediate values the percentage of screen loading to anode loading is defined as the square of the voltage ratio between signal voltage at the screen, and signal voltage at the plate. Percentage screen loading may thus be defined as the percentage of plate circuit signal power transferred to the screen. It should be noted that power is transferred to the screen only over part of the signal cycle, i. e. when the absolute value of plate potential falls below the absolute value of screen potential. This transfer has the effect of linearizing the plate characteristics.

It is found, for example, that with tubes of the 6L6 type, operating Class AB₁, the internal impedance of the tube drops very sharply as one proceeds from zero screen loading, but levels off at a very low value beyond about 18% screen loading. Maximum undistorted power output falls only slightly out to about 18% loading, and is very high, but beyond that value drops fairly rapidly. Low level distortion decreases rapidly from 0% to 18% loading, and far less rapidly thereafter. High level distortion is low out to 18% loading, but increases rapidly as loading is further increased.

It follows that with properly proportioned screen loading, depending on tube type, a tetrode can provide the high output power normally associated with tetrodes, but with low internal impedance, with very little more low level distortion than is produced by a triode, but with much less high level distortion.

In effect, then, we have provided a new tube type, which is neither triode nor tetrode, but which possesses advantages of each, and which is of increased linearity. The latter effect can perhaps be simply explained as a
straightening of the plate transfer characteristics of a triode, which are concave upward, by virtue of the plate transfer characteristics of the tetrode, which are concave downward. Whatever the true explanation, the plate transfer characteristic of the tetrode arranged in accordance with our invention is remarkably linear.
Because the Screen-Grids are supplied with DC from taps on the output transformer, the ultra-linear configuration therefore avoids the need for a separate Screen-Grid supply.

The third illustration shows the Acrosound Ultra-Linear design, also by Hafler and Keroes, which features a separate and lesser voltage supply to the Screen-Grids for improved performance and cooler operation.

The ultra-linear output configuration is also suitable to single-ended output stages, however only push-pull amplification is discussed in
this paper.

How It All Began

One authority, F Langford Smith of Radiotron Designers Handbook fame, attributes the original design concept to a pair of Australia inventors, R. Lackey and R.R. Chilton of the Australian Radio College, however the documented evidence has been lost. (If any reader has that information please email it to me)


Blumlein's Patent specified an optimum feedback tapping ratio being between 25 and 50% of plate output voltage to the Screen Grid, however he did not use either of the terms "Ultra-Linear" or "Distributed Load" in his Patent.

The much later detailed work of D. Hafler and H. I. Keroes of Acro USA (1951) demonstrated the optimum feedback voltage ratio to the Screen Grid for a range of defined tube types.

To our benefit, they published a paper on the topic in the November 1951 edition of "Audio Engineering" magazine.

Specifically, the 6L6, 807and KT66 families prefer a Screen-grid load of 18.5% Plate load impedance. (43% turns or 43% Plate Voltage).

Interestingly, they also claim the 6V6 family prefers a Screen-grid load of 5% Plate load impedance. (22.5% turns or 22.5% Plate Voltage).

This concept is fully described in US Patent 2710312, dated June 7, 1955. History shows Hafler and Keros successfully patented in the USA a further development of the general concept that had already been patented by Blumlein in the UK, had run most of its full term, then expired (maybe not quite, because the H and K application was lodged May 20, 1952). Their claims included a level of impedance loading to the Screen Grids of between 5% and 26% Plate Impedance - a much lower range to that of Blumlien.

This ratio was later verified by other respected designers, including GEC/MOV, GE USA and RCA

See also the thoughts of Norman Crowhurst.

Of particular interest is the Australian work of F Langford-Smith (of Radiotron Designers Handbook fame) in 1955, which investigates the Ultra-linear concept in detail for a range of tube types.

See AWV Radiotronics Magazine May and July 1955

It is worth noting that the original Blumlein Patent would have remained in force until 1953, so not much would have - or could have - happened regarding practical implementation of this technology in commercial products by other than Blumlien until after that date.

However, long before Blumlein's patent expired, he was killed in the year of 1942 in an aircraft crash whilst testing a new British radar design. Thus we can only speculate as to what might have been had he survived. It would be reasonably safe to assume that hi-fi audio would have been allocated a very low priority during the years of WWII during which Britain was struggling to survive.

Further reading on the life and times of this remarkable man is available at http://en.wikipedia.org/wiki/Alan_Blumlein

Since the famous "Williamson" amplifier design appeared some years after that date, it is reasonable to assume the "ultra-linear" concept was either safely locked away, or rejected by the gurus of the time in favour of triode mode. In fact, Williamson not only rejected the term but openly condemned the concept altogether - see Williamson and Walker - Wireless World 1952.

Thus the term "Ultra-Linear" may be rightfully attributed to Hafler and Keroes - an opinion supported by the "Radiotron Designers Handbook 4th Edition. This is the term used in their 1955 US Patent 2710312 (Application date 20 May, 1952) and is supported in that Patent by technical justification for use of the term.

In contrast to the above documented evidence, some researchers claim the Ultra-Linear concept was previously used in Australia as far back as 1933.

The question is - "How many ways is it possible to configure a 4 electrode device in an electronic circuit?"

Of course the answer is that someone, somewhere, at sometime will figure it out.

The famous Williamson triode-connected beam power tube amplifier was later modified by Hafler and Keroes to incorporate the ultra-linear design concept. Details are provided in their paper "Ultra-linear operation of the Williamson Amplifier" by Hafler and Keroes, published in the June 1952 edition of "Audio Engineering" magazine. It seems then that they had the last word, by improving Williamson's design despite his dismissal of the concept.. Numerous examples of this particular design are now available on the internet.
The Ultra-linear configuration in audio amplifiers is also known as "DISTRIBUTED LOAD" operation.

It appears this term was introduced by Williamson and Walker of the UK, who objected to the term "ultra-linear".

Of course this term is also technically correct, because the taps on the output transformer primary do in fact present a push-pull reactive load to the Screen Grids, enabling them to contribute to useable power output. This is explained in detail in the Hafler and Keroes Patent.

However importantly, Mullard describe the "distributed load" configuration as a system of negative feedback.

The term "distributed load" was adopted by Mullard as corporate policy. Their use of this term was published in the May and June 1955 editions of "Wireless World" in their article "Design for a 20 Watt High Quality Audio Amplifier".

It is interesting to note that this design appeared from Mullard, notwithstanding Williamson's previous condemnation of the concept.

I am unable to verify the specific designer of the 5/20 amplifier but later credits go to Mullard Applications Research Laboratories Engineers Mssrs R. S. Babbs, D. H. W. Busby, P. F. Dalloso, C. Hardcastle, J. C. Latham and W. A. Ferguson. (No mention of Williamson and Walker). It is assumed the commercial pragmatists won the argument.

Mullard continued to use this term through until at least the 1960's when their compendium of audio amplifier and pre-amplifier circuits "Mullard Circuits for Audio Amplifiers" was published as a second edition reprint in 1962.

The following extract from that publication provides an overview of Mullard's design concept.
Distributed Loading

The conditions of distributed loading are achieved by applying negative feedback in the output stage itself. In the simplest form of distributed-load operation, the screen grids are fed from suitably positioned taps on the primary winding of the output transformer, and the stage can be considered as one in which negative feedback is applied in a non-linear manner via the screen grids.

The characteristics of the output stage under these conditions of operation lie between those for pentode and triode operation. They approach the triode characteristics as the percentage of the primary winding common to the anode and screen-grid circuits increases. Under optimum conditions, about two-thirds of the power-handling capacity of the corresponding pentode stage can be realised with a much lower level of distortion while, at power levels corresponding to triode operation, the distortion also is of the order corresponding to triode operation. At the same time, the output impedance is reduced to a level approaching that obtained if a conventional triode push-pull stage is used.

An output stage with distributed loading can thus be used with pentodes of the 25W type in high-quality amplifiers designed for output powers well in excess of 15W, the power efficiency being appreci-
ably greater than with triode operation. Alternatively, the performance of 12W pentodes can be improved considerably and, although the power handling capacity is reduced somewhat, effective output powers of 10 to 12W can still be obtained.

A comparison is given in Table 1 of triode, pentode and distributed-load operation for the Mullard output pentodes, types EL34 and EL84. For the EL34, the comparison between distributed-load operation and triode operation is of most interest. It will be seen from this that distributed-load operation using a tapped-primary output transformer enables the power-handling capacity to be more than double that possible with triode operation whilst, at the same time, distortion in the stage can be kept very low.

Although with a common-winding ratio of 0.2 (that is, with 20% of the primary winding common to the anode and screen-grid circuits) the distortion level is comparable with triode conditions, it has been
found that appreciable improvement is obtained at higher output powers if the ratio is further increased. Progressive improvement has been obtained as the percentage of common primary winding is increased up to 40 or 45%. The power-handling capacity of the stage is reduced further as the ratio is increased, but at least 35W can be obtained with a level of distortion at the onset of grid current of about 2.5%.

Typical performance curves of the EL34 when used with an output transformer having the primary winding tapped at 43% of the turns are shown in Fig. 3. The output powers quoted are those delivered to the load in the secondary circuit.

With valves of the 12W dissipation class, comparison with normal pentode operation is more significant. Appreciable reduction in odd-harmonic distortion is again obtained under distributed-load conditions, and an output of approximately 15W is delivered by the valves if the common winding ratio is 0.2.

For an excellent technical introduction to the ultra-linear design concept see http://www.aikenamps.com/UL.pdf

More technical detail, single-ended ultra-linear circuits and non-power tube ultra-linear applications is also available from Glass Audio - "Tube CAD Journal" Vol. 2 No. 1 - January 2000

For further views and technical details see also http://www.vintageradio.me.uk/amplifier/10watt.htm

Important Note: Performance described as “ultra-linear” is available only under very specific operating conditions - and in the case of popular commonly used audio tubes, usually where the Screen load is 18.5% impedance or 43% turns of the Plate load impedance - measured from the power supply source (B+) terminal.

More detailed information is provided below.

In other cases, the term "distributed load operation" may be more appropriate.

Tube Operating Conditions:

The attached graphs, courtesy of GE USA, show the marked difference in operating conditions for pentode, triode and ultra-linear operation of the 6550 Beam Power Tube.

6550 Beam Power Tube Operating Conditions - Pentode Connection
AVERAGE PLATE CHARACTERISTICS

PLATE VOLTAGE IN VOLTS

SCREEN CURRENT (Ic) IN MILLIAMPERES

PLATE CURRENT (Ib) IN MILLIAMPERES

6550 Beam Power Tube Operating Conditions - Triode Connection
6550 Beam Power Tube Operating Conditions - Ultra-Linear/Distributed Load Connection
Benefits:

The *ultra-linear* configuration ensures constant stage specific voltage feedback between Plate and Screen grid in the output stage, thus reducing output impedance and distortion, whilst improving linearity and frequency response under variably reactive loudspeaker load conditions.

An important advantage is that being single stage-specific, *ultra-linear* operation avoids the problems of time-delay and phase-shift commonly associated with cascaded stage amplifiers using negative feedback from the loudspeaker for the purposes of reducing distortion and increasing loudspeaker damping.

*Ultra-linear* output stages provide automatic constant ratio stage-circuit specific feedback, free from the adverse effects of conventional multi-stage feedback systems.

*Ultra-linear* output stage power output is dependent upon the proportion of Plate load that is applied to the Screen-Grids - typically in the range 75% to 100% that of tetrode/pentode connection at the same plate voltage - but is still twice triode connection for the same tube type under the same operating conditions.

*Ultra-linear* tone or "sound" approximates that of triodes.

*Ultra-linear* operation is very forgiving of circuit design and generally provides an acceptable quality sound from average quality output transformers. Note however that the esteemed Norman Crowhurst, in a November 1959 "Audio" Magazine article entitled "Puzzled About Amplifiers", indicates that a high-quality output transformer is essential for *ultra-linear* operation, to ensure high-fidelity performance over the entire audio frequency range.

To this end, Herbert Keroes of Acrosound developed a special transformer for ultra-linear configuration output stages. The main purpose of this transformer is to enable the use of transmitting tubes, where the Screen-grids must operate at a significantly reduced
DC voltage to that on the Plates. Full specifications are provided in US Patent 2791646 (May 7 1957).

A set of high-fidelity amplifier designs was published in the Acrosound Ultra-Linear Transformer Catalogue, published a little later. The flagship of the range - the TO350 - offers 100W from a pair of 6146 tubes. This is an exceptional amplifier by any standard.

**Design Concept:**

A good example of a typical conventional *ultra-linear* circuit is shown in the [GEC KT88 100W Amplifier](#).

A more highly developed design is shown in the [GEC KT88 400W Amplifier](#).

The conventional *ultra-linear* configuration is arranged such that the screen grids have maximum DC voltage applied to them (in practice slightly higher than their corresponding plate/anode voltage because of voltage drop in the primary winding) - thus maximising power output and efficiency, whilst simultaneously receiving an AC negative feedback signal from the output transformer - thus minimising output impedance and distortion.

The magnitude of the AC feedback signal is directly proportional to the percentage turns ration of screen tap to full winding.

The screen tap may be positioned anywhere from 0% (pentode connection) to 100% (triode connection), however performance and tonal qualities change relative to the ratio of the screen tap - see GEC graph below.

In practice, research by the inventors of this method of amplifier configuration suggests that the ideal for most tube types is in the range 40 to 50% turns of each half primary, measured from the primary centre tap.

Further research by Mullard UK for the EL34/6CA7 and EL84/6BQ5, GEC/MOV Valve Co. for the KT88, GE USA for the 6550, and RCA for the 6973 (6CZ5 hi-fi), 7027A (6L6GC), 7591, 7868 (6L6 family), also recommends 43% turns (or 43% of plate signal voltage), or 18.5% impedance.

An example of EL34/6CA7 operation with cathode bias is shown in the following graph - courtesy Amperex Electronic Corporation
**Screen-Grid Operation:**

One very important feature of the *ultra-linear* configuration - different to normal Tetrode/Pentode operation where both Screen-Grids are at nominal AC earth potential - is that when one Screen-Grid in a push-pull pair is driven positive, the opposite Screen-Grid is driven negative by the turns ratio of the output transformer acting about the centre-tap of the transformer, which is at nominal AC earth. This is not a problem because the opposite Plate is also being driven negatively anyway by the action of the push-pull driver/phase splitter.

The opposite applies when the alternating signal reverses polarity.

In Class B operation, the output transformer operates as an auto-transformer, so the opposite Plate and Screen-Grid are still driven to opposite polarity (together in a constant ratio to each other), even though they are not conducting.

---

**Balanced Amplifier**

It should be noted that in the case of a push-pull amplifier, the DC negative bias voltage (even if it is at 0 VDC) applied to the Control Grid #1 is located at the centreline axis of the **balanced** input signal. This means the inputs are floating and the centre-axis is earthed. That is to say, the input Grids are being driven in a push-pull manner about a common centre-point or axis - eg as seen with a centre-tapped push-pull driver transformer.

Thus in a conventional push-pull Tetrode or Pentode amplifier, any alternations of the balanced input signal to the Control Grids will proportionately increase or decrease current flow in both tubes of the push-pull pair in response to the input alternating waveform shape.
Now in each tube of a push-pull pair, the negative terminal (Cathode) of each tube is AC earthed - even in Cathode bias.

The load on each tube is connected between the Plate and the transformer centre-tap, so the negative terminal of the load - which is at the output transformer centre-tap - is also effectively AC earthed.

But most importantly to ultra-linear operation, in a push-pull amplifier output stage, Screen-Grid behaviour will be similar to that of Grid #1 - ie the Screen-grids will behave as a balanced amplifier - balanced about the centre-tap of the output transformer which, as previously noted, is effectively AC earthed - ie variations in Screen-Grid voltage will produce proportionate variations in electron flow in both output tubes simultaneously.

In conventional Tetrode and Pentode operation, when the DC applied voltage to the Screen-grids is constant, the AC voltage appearing at the balanced Screen-Grid terminals will be the product of the electron flow within each tube and will always be a voltage determined by the natural AC voltage gradient applied internally across each tube.

Also in a conventional Tetrode/Pentode output stage, the AC signal voltage appearing at the Screen-Grids is diverted to AC earth at the Screen-Grid terminals via the filter capacitor and is lost as heat. Hence the output voltage appearing at the Screen-Grid terminals is of no consequence to the sound produced by the amplifier - ie it is not reproduced in the output transformer or loudspeaker.

However, in the case of the Screen-Grids in ultra-linear push-pull amplifier configuration this is not so, because the Screen-Grids are located at about 43% of the lineal distance between Cathode and Plate. Thus the AC signal voltage appearing at each Screen-Grid as a result of linear voltage gradient between the Cathode and Plate within each tube will thereby be about 43% of the Cathode to Plate signal voltage.

The Screen-Grids are connected to the load so they will contribute to the sound produced by the amplifier.

**Class A and Class B Ultra-Linear Operation**

In some transmitters, it has been the practice to drive or control the output power tube by means of the Screen-Grid, rather than the Control Grid.

This method offers some benefits to RF situations but is relevant to the explanation of ultra-linear audio amplifiers.

Because the Screen-Grid is located much further into the physical Cathode to Plate distance - ie typically nearly centrally between them - it follows that a substantially higher AC signal voltage must be applied to the Screen-Grid if that element is to control the electron flow in the tube.

Operation will be the same as for Grid #1 but at a higher AC voltage.

It follows that if the DC Screen-Grid voltage controls electron flow within the tube and it is varied by means of a superimposed AC voltage, then the Plate Current will vary in response - as for conventional Grid #1 operation.

But what if the Screen-Grid voltage is applied in 180 degrees directly opposite phase to the electron stream within the tube - as is the case for ultra-linear operation?

Obviously the electron stream permitted by the AC signal as applied to Grid #1 is offset by the opposing signal voltage applied to Grid #2 via the tapping on the output transformer - because they are both in the same circuit at the same time.

Consequently behaviour of the tube in response to the controlling signal voltages applied to BOTH Grid #1 and Grid #2 simultaneously, will be different to that of either a Triode or Tetrode.

This is what the above GE graphs demonstrate - ie a change in the operating characteristics of the basic tube, verifying the claim of Hafler and Keroes that they had produced a "virtual" tube, intermediate between a triode and a tetrode.

The situation is however very different between Class A and Class B operation.

In the case of Class A ultra-linear operation, the Screen-Grid of one tube will be driven AC positive but the Screen-Grid of the opposite tube will be driven to an equal, but opposite polarity, voltage by the output transformer balanced output about the AC earthed centre-tap. This will have the effect on the second tube of reducing the effective Screen-Grid control voltage, thereby reducing voltage gain and therefore power output - regardless of the shape of the input waveform to that tube.

But also note that Grid #1 of both tubes is also controlling current in them.

Hence in Class A ultra-linear operation, it is necessary to consider the effects upon Cathode current in BOTH output tubes by BOTH Control Grids and BOTH Screen-Grids.

However in the case of Class B ultra-linear operation, although the second tube will be similarly driven to reduce its gain, there is no signal in it at that moment in time because its Control Grid #1 is at cutoff bias during the relevant half-cycle of signal input so zero or near zero current is flowing in that tube.
Thus a Class A ultra-linear amplifier will have completely different behaviour to a Class B ultra-linear amplifier.

Distributed Load Operation

On the other hand, that portion of the output transformer primary winding between the Screen-Grid tapping and the centre-tap is not subject to cancelling out by out of phase signal in the power circuit.

This portion of the winding - usually 18-19% Plate to Plate load impedance - therefore imposes a load directly onto the Screen-Grids.

Thus a portion of the power output is delivered through this Screen to Screen winding.

However, although the winding and its corresponding load impedance is presented to the Screen-Grids, they are incapable of delivering much power because the Screen-Grids will be aligned in the electron stream such that the small diameter grid wires are not directly in the electron stream - so because of space-charge effects cannot attract electrons.

Furthermore, the Screen-Grids are charged to opposite polarity to the electron stream during half of each signal alternation cycle, which further detracts from their electron collecting capability.

For the record, in their US Patent 2,710,312 Hafler and Keroes state: "It should be noted that power is transferred to the Screen only over part of the signal cycle, i.e. when the absolute value of Plate potential falls below the absolute value of Screen potential. This transfer has the effect of linearizing the Plate characteristics."

Power Output

*Ultra-linear* operation typically (for the popular audio tube types) delivers 100% power output compared with the same tubes in tetrode or pentode connection at the same plate voltage and bias system (GEC) - but sometimes less for other tube types.

For example, Mullard quote the power output for the EL34 tube as being the same for pentode and ultra-linear connection with 20% turns screen-taps, but for minimum distortion the screen-taps increase to 43% turns, which provides a power reduction of 15% (but distortion is halved).

Note: Worthy of note is the KT88, which GEC (MO Valve Co./Genalex) claim produces the same power in *ultra-linear* connection as in Pentode connection at 43% turns. This may be due to the applied Screen-Grid voltage used in *ultra-linear* operation being twice the recommended value as that for Tetrode operation. *Importantly, the electrode structure of the original GEC-MOV KT88 is internally physically identical to the GEC TT21 and TT22 RF transmitting beam power tubes, so the GEC-MOV made KT88 is therefore capable of operating at its rated 600 VDC maximum Screen-Grid DC operating voltage continuously without distress.*

The TT21 or TT22, which have a top anode cap and intended for professional broadcast use, may be used in lieu of the KT88 as a direct electrical substitute. Grid to plate capacitance is reduced, which should produce superior audio performance over the KT88.

One of the challenges to the home constructor is that manufacturers’ tube manuals and data sheets often quote "typical operation" for fixed bias pentode connection but cathode-bias for *ultra-linear* connection.

Ultra-linear Circuit Characteristics:

The following graph, courtesy of GEC and AWV *Radiotronics* Magazine (May 1959), shows the comparative characteristics of the KT88 in triode, pentode and ultra-linear connections. These comparative relationships between the different connection configurations should be typical for most (but not all) tetrodes, pentodes and beam power tubes.
Note:

- the relationship between output impedance and ratio of screen tap turns.
- the relationship between output power and ratio of screen taps.
- the relationship between THD distortion and ratio of screen taps.
- the effect of load impedance upon output power.
- the power output for ultra-linear operation is greater than that for pentode or triode operation.

This graph shows that for ultra-linear operation the original GEC/MOV KT88 is unsurpassed!!

**WARNING: 6550 V KT88**

- Although having identical general specifications the 6550 Beam Power Tube - its USA cousin, has **substantially lower**
  electrical ratings for pentode, triode and **ultra-linear** connections - so be warned!!
- Although the 6550 and KT88 are often specified in tube handbooks and amplifier schematics as equivalent substitutes for each other it may be wise to check the ratings first before making a change from KT88 to 6550.
- Physically, some brands of 6550 tubes have a parallel glass envelope smaller in diameter than the KT88 so there may be inadequate space to instal the KT88 or to provide adequate natural air cooling without major modification. The reverse change is electrically not a problem.
- Although the KT88 is derived from the TT21 and TT22 transmitting tube stable, the origin of the 6550 is not clear.
- Some users have reported detailed examination of certain Russian made KT88 and 6550 tubes suggests they are physically identical but branded for use as either KT88 or 6550 thus it is wise to check the manufacturer’s specifications before installation in any high voltage circuit.

**WARNING:**

- The GEC/MOV KT88 octal socket centre base spiggot is made from a brittle plastic moulding material and tends to break off if the tube is not inserted and removed very carefully from its socket. This tube is big and heavy in relation to its octal base so is unsuited to horizontal or inverted mounting unless retained by a suitable device.
- The GEC/MOV KT88 was typically made with one or two base pins omitted (presumably to save on cost) that has the effect of
increasing stress on the remaining pins whilst providing a less secure installation.
- Do not use the KT88 in inverted mounting without a retaining device.

**EL34/6CA7 Ultra-linear Circuit Characteristics:**

The following graph by Mullard UK shows performance of the EL34/6CA7 valve.

![Graph showing EL34/6CA7 Ultra-linear Circuit Characteristics](image)

*Fig. 3—Performance characteristics of two EL34 in pentode-connected push-pull arrangement under conditions of distributed load*

Note the comparative "linear" performance for power out v distortion over a wide range of loads and similar operating conditions.

Further information is provided by the following table ex Mullard UK, that shows comparative performance between the Mullard EL34...
Recent Research

I am indebted to Rudolf Moers, a distinguished Electrical and Electronics Engineer located in the Netherlands, who has made available for us his wonderful recent scientific investigation into the design theory and practice of Ultra-linear audio amplification.

These papers are posted with permission from Linear Audio www.linearaudio.net and their author Rudolf Moers.

**Part 1 - Power Point presentation**

**Part 2 - Power Point presentation**

**Parts 1 and 2 of above Power Point presentation - combined in pdf format**

**Paper - The Ultra-Linear Power Amplifier: An adventure between triode and pentode - pdf format**

The engineering design methods developed by Mr Moers may be used to determine theoretical plate/screen load ratios for ultra-linear operation of power tubes.

**Application:**

In practice, for tube types other than KT88, the real loss of useable output power from the *ultra-linear* connection is actually significantly less than any power differential measured with resistive loads might suggest (ie a 1.5 db reduction in loudness produced by the loudspeaker), because the *ultra-linear* connection produces a higher coupling efficiency between the amplifier and loudspeaker than tetrodes or pentodes - ie is more triode like - thus approximating an equivalent "loudness" to pentode connection.

This phenomenon is particularly true of low frequency reproduction, suggesting that *ultra-linear* connection is superior for double bass violin, bass guitar and general hi-fidelity reproduction down to about 40 Hz - which is the lowest musical frequency normally reproduced in popular music.

<table>
<thead>
<tr>
<th>Valve</th>
<th>Mode of Operation</th>
<th>Operating Conditions</th>
<th>Total Distortion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$V_{ae}$ (V)</td>
<td>$V_{ez}$ (V)</td>
</tr>
<tr>
<td>EL84</td>
<td>Triode connection</td>
<td>400</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Distributed load</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>$a$ 20% common winding</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>$b$ 43% common winding</td>
<td>330</td>
<td>330</td>
</tr>
<tr>
<td>EL34</td>
<td>Triode connection</td>
<td>300</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>Distributed load</td>
<td>300</td>
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<td></td>
<td>$a$ 20% common winding</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>$b$ 43% common winding</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>Pentode connection</td>
<td>300</td>
<td>300</td>
</tr>
</tbody>
</table>

*Screen grid strapped to anode*
The 6L6 family of tubes can be used for *ultra-linear* connection, but only safely and reliably at reduced voltages not exceeding rated screen-grid voltage. More suitable 6L6 style types include 5881 and 7027A - see manufacturers' data sheets for typical circuit values.

*Ultra-linear* operation typically delivers about two to three times the power output compared with the same tubes in triode connection at the same plate voltage.

Most importantly, inter-modulation distortion is substantially lower with *ultra-linear* connection compared with pentode or triode connection for the same tubes.

Note: In the case of hi-fi systems, percussive instruments such as the bass drum, tympany, harpsicord, guitar and the piano present typically short-duration/transient low fundamental frequency signals rich in harmonics. Thus they are less demanding to reproduce than the electronic organ, pipe organ or bass guitar, which produce an essentially long-duration signal, approximate to a sine wave, in the lower register.

Triode connection is still the preferred option for seriously loud organ music because of the lower frequencies to be reproduced, the need for "boom" free bass around the loudspeaker resonant frequency and, most importantly, a need for consistent gain (flat response) throughout the musical scale to ensure all notes are reproduced with equal loudness when they are recorded that way. However triodes deliver substantially higher intermodulation distortion than *ultra-linear* operation so adequate power headroom is essential to ensure clear mid to upper range reproduction simultaneously with sustained lower register signals.

A major advantage of *ultra-linear* connection over tetrodes and pentodes is the improvement in tone for recorded music and public address reproduction. The tone is more triode like, being smooth and mellow (but "clearer" than triodes), compared with the harsh tone of tetrodes and muddy tone (read "less definition") of pentodes.

**Guitar Amplifiers:**

*Ultra-linear* operation is not usually suitable for lead guitar amplifiers because it lacks the "crispness", "harshness" or "bite" in the sound commonly provided by beam power tetrodes and pentodes, however some jazz and country music guitarists may find it preferable where a smooth, natural mellow tone is sought.

However, *ultra-linear* operation is superior to tetrode/pentode connection for bass guitar applications because low frequency power delivered to the loudspeaker is substantially greater - ie it is "louder" - due to lower output impedance and improved coupling to the loudspeaker.

It also has a "deeper" tone, suggesting improved sub-harmonic performance.

**Summary:**

In summary, *ultra-linear* connection offers:

- useable power output approaching that of tetrodes and pentodes but with substantially reduced harmonic and intermodulation distortion and improved tonal characteristics, thus making it the preferred configuration for high-fidelity applications.
- a "warmth" of tone, not evident with the "clinically clean" sound of *unity coupling*, where the load is distributed between plate and cathode.
- simplicity in circuit design and construction
- elimination of need for a separate power supply to the screen-grids
- employment of a simple output transformer
- constant-voltage negative feedback
- high stability operation over a range of reactive and capacitive loads
- strong useable low-frequency power output - ie as heard through the loudspeaker
- good dynamic range performance and transient response

*Ultra-linear* operation also enables lower quality loudspeakers to be used for satisfactory results.

Note that in high power applications - ie more than 100W RMS, transmitting *TRIODE* tubes such as 805, 809, 810, 811, 812, 833, 845, 8000, 8005, etc may be a more economical and practical solution than trying *ultra-linear* configuration with tetrodes/pentodes because of simplified wiring, output transformer and power supply requirements.

**TUBES FOR ULTRA-LINEAR OPERATION**

The "*Ultra-linear" configuration avoids the conventional conflict between plate and screen voltages by creating a voltage divider network through the output transformer primary to AC earth (transformer centre-tap), ensuring the screen voltage tracks and thus always remains, both below and proportional to the plate signal voltage. By this configuration, the screen is intended to be prevented from exceeding its power dissipation rating.
For high power applications where high plate voltages are needed, success may be achieved by adding a separate winding from the DC plate supply, thus enabling the screens to be supplied within their rated voltage from an independent supply.

Applied plate (B+) voltage for ultra-linear connection should never exceed Grid 2 rated voltage, so standard ultra-linear configuration is only suited to tubes designed for audio applications having a Grid 2 rating approximating either the plate voltage rating (or actual applied plate voltage if less than rated maximum).

Important: Reference to tube data sheets will show that few output tubes have ratings remotely matching this requirement.

Important: The use of poor quality output transformers having a high DC resistance in the primary windings may establish a situation whereby the actual DC Plate voltage drop across the transformer primary winding is high, causing the DC Screen-Grid voltage to be higher than the Plate at high signal levels.

Unfortunately, only a small number of tube types are thereby suitable for ultra-linear operation, because in ultra-linear mode the screen grid is operating at or above the plate voltage - a dangerous operating region for any tube.

Only a few tube types were recommended by their manufacturers as being suitable for ultra-linear connection, the most notable being EL34/6CA7, EL84/6BQ5, KT88, 6550, 7027 and 8417 - see manufacturers' data sheets for typical circuit values.

In a typical output tube, the Screen Grid is the ANODE, or positive electrode. It is designed to accelerate electron flow from Cathode to Plate, but is structured in such a way that most electrons pass through it and on to the Plate for collection.

Excessive screen grid voltage attracts excessive electrons to it, thereby resulting in excess grid current, excessive grid power input/dissipation, overheating and melting. The fused screen grid wires may short-circuit B+ to earth, damaging the output transformer and/or power supply components.

Unfortunately, most audio tetrodes, pentodes and beam power tubes are designed such that the Screen Grid may be operated only up to a maximum DC voltage that is well below the Plate voltage - typically 150 to 300 volts.

Plate current is very much controlled by the Screen Grid, thus when the Screen Grid is made ineffective (ie over-active) by application of excessive voltage, the Plate Current is likely to exceed the tube ratings and also melt the plate.

Another way of saying this is that if the Screen Grid voltage is excessive, the capability of Grid #1 (Control Grid) to control electron flow in the tube is diminished - or lost altogether.

Operation of typical power tubes (having a screen grid voltage rating substantially lower than the rated plate voltage) in ultra-linear connection is likely to result in loss of control over electron flow by the screen, resulting in thermal runaway or dynatron action - resulting in self-destruction of the tube. Fire is a constant risk.

For example, tubes designed for RF power service typically have a plate voltage rating many times higher than their corresponding screen grid voltage rating. This class of tube (eg 807, 2E26, 6146, 4CX series) has the screen grid physically positioned close to the control grid (Grid 1) and tend to self-oscillate or suffer thermal runaway when the screen grid voltage is higher than their rated screen-grid voltage, which is always the case with conventional ultra-linear service, thus rendering them unsuitable for ultra-linear service.

WARNING: When using tubes fitted with a plate top cap (anode cap) in ultra-linear configuration, consider also the risk of self-oscillation and/or parasitic oscillations from the combination of long leads from the plate top caps and screen grids to the output transformer - particularity significant when using multiple tubes to obtain higher power. Some of this lead length may be avoided by chassis layout however in the case of top cap style tubes the screen connection is always under the chassis, thus ultimately requiring connection in some way from top to bottom of the tube through the output transformer.

High Power Output:

Where more power is needed it is preferable to use a larger tube that is known to be more suited for ultra-linear circuitry, such as the KT88, KT90 or 813.

Another useful option is to run multiple pairs of tubes in parallel push-pull, such as the arrangement used in the GEC 400W KT88 Amplifier. It goes without saying that normal precautions against instability and parasitic oscillations are essential in layout, lead dress, use of grid stopper resistors wired directly to the pins, and keeping inputs away from outputs. The output transformer must be of high quality with low leakage capacitance and low leakage inductance between windings. Tubes should be mounted close together to minimise inter-connecting lead length. Grid #1 circuit resistance must be held within the manufacturer's ratings. A low-impedance driver, such as a cathode-follower or transformer is recommended.

For high power applications where high plate voltages are needed, success may be achieved by adding a separate winding for each screen grid to the output transformer, to enable the screens to be AC coupled to the plates thus providing ultra-linear operation, but separated from the DC plate supply, thus enabling the screens to be supplied within their rated voltage from an independent supply.

The ACROSOUD 100W Ultra-Linear Amplifier using 6146 tubes and the TO-350 Transformer is an example of this excellent and innovative design configuration.
One of the benefits of this configuration is that the Screen-Grid supply can be independent to the Plate supply and therefore better regulation can be incorporated into the Screen Grid circuit. Noting the Screen-Grid is the ANODE in a Tetrode or Pentode tube, a regulated supply will deliver improved transient response and a “brilliance” to the reproduction not available with a common B+ power supply as is the case in conventional Ultra-Linear operation.

Bruce DePalma, one of the few Gurus of modern hi-fi amplifier design, presents an interesting and comprehensive commentary on the core design philosophies supporting this approach in his excellent Design Paper - "Analog Audio Power Amplifier Design".

Bruce has developed designs that enable both Ultra-Linear and low Screen-Grid voltage technologies to be successfully integrated in such a way that extremely hi-fi performance results.

BIAS

Grid 1 bias for ultra-linear operation is normally higher than that for tetrode/pentode connection, so output stage sensitivity is reduced. Higher output voltage from driver stages is therefore needed.

Grid-stopper resistors to Grid #1 and Grid #2 are still required for ultra-linear operation.

Important: The technique of using a silicon rectifier diode on each Screen Grid in series with the Grid-stopper resistor, as described in my "OPTIMISED ULTRA-LINEAR ©" page, is very helpful in ultra-linear connection. AC signal output voltage from the Screen-Grids is prevented from conducting through to the output transformer, which means that the ultra-linear output stage operates as a negative feedback system only - ie Plate voltage is fed back to the Screen Grids via the transformer taps but not the other way around. This method ensures all the electron flow goes to the Plates, with all the advantages described previously.

Note: This configuration has opposite polarity as when zener diodes are installed to reduce screen-grid voltage, so therefore the benefits described are not relevant to the zener diode technique.

Important - When using a high B+ voltage:

To ensure Plate Dissipation remains within manufacturer's rating at both zero and maximum signal, it may be essential to use Class B operation - thus introducing further complexity into the circuit design and perhaps offsetting much of the benefit offered from the ultra-linear configuration. It may be more prudent to use a tube having a higher rating.

RECOMMENDED TUBES

The following tubes are known to be suitable for conventional ultra-linear operation having nominally equal Plate and Screen-grid DC supply volts:

<table>
<thead>
<tr>
<th>TUBE TYPE</th>
<th>MAX. ULTRA-LINEAR CONNECTION PLATE TO CATHODE VOLTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>6AQ5A</td>
<td>285</td>
</tr>
<tr>
<td>6BM8</td>
<td>300</td>
</tr>
<tr>
<td>6BQ5/EL84</td>
<td>300</td>
</tr>
<tr>
<td>6BW6</td>
<td>285</td>
</tr>
<tr>
<td>6CA7</td>
<td>500</td>
</tr>
<tr>
<td>6CM5/PL36</td>
<td>250</td>
</tr>
<tr>
<td>6CZ5</td>
<td>285</td>
</tr>
<tr>
<td>6L6GB</td>
<td>270</td>
</tr>
<tr>
<td>6L6GC</td>
<td>400</td>
</tr>
<tr>
<td>6V6GT</td>
<td>285</td>
</tr>
<tr>
<td>5881</td>
<td>400</td>
</tr>
<tr>
<td>6146A, B, W etc</td>
<td>250 (Top cap style)</td>
</tr>
<tr>
<td>6550</td>
<td>450 (Note: GE USA &quot;design maximum&quot; rating. Some brands may not tolerate this voltage)</td>
</tr>
<tr>
<td>6973</td>
<td>300</td>
</tr>
<tr>
<td>7027A</td>
<td>450</td>
</tr>
<tr>
<td>7189A</td>
<td>400</td>
</tr>
<tr>
<td>7581</td>
<td>450</td>
</tr>
<tr>
<td>7591</td>
<td>400 (50% turns recommended by RCA)</td>
</tr>
<tr>
<td>7868</td>
<td>400 (50% turns recommended by RCA)</td>
</tr>
<tr>
<td>807/5B-255M</td>
<td>300 (Top cap style)</td>
</tr>
<tr>
<td>8417</td>
<td>500</td>
</tr>
<tr>
<td>EL34</td>
<td>425</td>
</tr>
<tr>
<td>EL84/6BQ5</td>
<td>300</td>
</tr>
<tr>
<td>KT66</td>
<td>400</td>
</tr>
<tr>
<td>8417</td>
<td>500</td>
</tr>
<tr>
<td>KT88</td>
<td>600 (Note: GEC UK &quot;design maximum&quot; rating. Some brands may not tolerate this voltage)</td>
</tr>
</tbody>
</table>
KT90  600  ("Absolute Maximum" rating)
813  1100  (This tube is an excellent option for serious audiophiles but has a top cap and requires a centre-tapped 10 V AC/DC filament supply - 5A per tube. External wiring must be screened to prevent RF induction and parasitic oscillations. Adequate ventilation is essential)

In my humble opinion, the most suitable candidates for ultra-linear connection are:

6CM5/PL36  (250 VDC)
6AQ5/6V6GT  (275 VDC)
6CZ5/6973   (285 VDC)
5881/6L6GC/7027A/7591/7868  (400 VDC)
KT88/KT90  (600 VDC) (may need to reduce to 450/500 VDC with non GEC manufacture)
813       (1100 VDC)

All are well proven fine quality beam power tubes - each famous in its own right.

Other options are the EL34 (425 VDC) or 6CA7 (500 VDC) or EL84/6BQ5 (300 VDC) pentodes, however in my opinion sound from these tubes is not as clean as those above. All of this family of tubes "sounds" similar because of their generally identical electrode construction.

If you have had successful experiences with other tube types that are useful for ultra-linear connection please email your comments.

For further information regarding Ultralinear operation of vacuum tubes see my OPTIMISED ULTRA-LINEAR © OPERATION page

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BACK TO HOME PAGE

This page last modified 16 April 2012
This page is located at http://www.oestex.com/tubes/ul.htm
Readers, please note this page is presented for your education, information and guidance only - it is not intended to be a technical/scientific treatise. The concepts and ideas presented herein are just as much subjective as objective.

It attempts to assist those experienced audiophile home constructors who wish to explore further tube amplifier development options and are prepared "to go beyond the square" - to challenge the paradigm of "the status-quo".

This paper refers only to the characteristics and performance of push-pull tube audio amplifiers without negative feedback.

For reasons detailed elsewhere in my website I have no interest whatsoever in single-ended amplifiers - however the concepts described herein are as equally applicable to single-ended amplifiers as to push-pull configurations.

For reasons detailed elsewhere in my website I have no interest whatsoever in the use of trans-stage negative feedback thus the concepts described herein are intended to optimise electron tube performance without the use of negative feedback.

For full ratings and applications of specific tube types in which you are interested please refer to the manufacturer's catalogue.

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1. INTRODUCTION

It is recommended that to best understand the concepts presented here, the reader first carefully study my explanatory papers. To directly access please click on each of the links below:

SCREEN-GRIDS
ULTRA-LINEAR
OPTIMISED ULTRA-LINEAR © OPERATION
TRIODE OPERATION OF TETRODES AND PENTODES
POWER SUPPLIES
HOW TO DESIGN AND CONSTRUCT A HI-FI TUBE AMPLIFIER

It is intended that the set of OPTIMISED ELECTRON STREAM © TECHNOLOGY concepts presented below represent - together as a set, an extension of design thinking to the above linked presentations elsewhere on my website, and a major breakthrough in electron power tube technology available to the home audio constructor.

Historically we have been restricted by convention to a small set of engineering design principles that have imposed a barrier to further development, reinforced by commercial manufacturers staying with the tried and true "safe" design configurations.

However the availability of low-cost high-performance transistor amplifiers and pre-amplifiers, together with advances in recording formats - currently DVD standards - have provided stimulus to tube hi-fi enthusiasts to improve the performance of their existing equipment.

Many of the old constraints are longer with us - hiss, noise, wow, flutter and rumble etc. do not present on CD or DVD - so enable us to open the frequency range and dynamic range window a little more.

The OBJECT of OPTIMISED ELECTRON STREAM © TECHNOLOGY is to OPTIMISE performance in a high-fidelity audio amplifier by simultaneously loading ALL the internal elements of a power electron tube with a load directly proportional to their ACTUAL applied voltages - AC and DC - as distributed between the positive and negative terminals of the tube - ie anode and cathode - AND in direct proportion to their physical electrode spacing (dielectric strength).

Hence OPTIMISED ELECTRON STREAM © TECHNOLOGY may also be described as OPTIMISED DISTRIBUTED LOAD © TECHNOLOGY

OES © TECHNOLOGY offers superior performance because it is simple and because the tube is always in equilibrium.

The conceptual model is illustrated in the following circuit diagram for Beam Power Tubes, Tetrodes and Pentodes:
OPTIMISED ELECTRON STREAM © TECHNOLOGY: SCOPE

This paper introduces eight new applied engineering OPTIMISED ELECTRON STREAM © TECHNOLOGY concepts for refining and optimising the electron flow in a vacuum tube.

- Optimised Screen-Grid Voltage and Load in Tetrodes, Pentodes and Beam Power Tubes
- Optimised Suppressor Grid Voltage and Load in Pentodes
- Silicon Diode Feed in Triodes, Tetrodes, Pentodes and Beam Power Tubes
- AC Circuit Bypass Capacitors - Plate Circuit, Screen-grids, Suppressor-grids, Control-grids, Cathode Bypass
- RATIO of Screen-grid and Suppressor Grid and Cathode Bypass to Plate Bypass Capacitors
- Decoupling of the Power Amplifier from the Power Supply by means of a series connected silicon diode
- Decoupling each amplifier stage from the next following by means of a series connected silicon diode
- Symmetrical balanced AC signal drive system whereby the central axis of the AC signal OUTPUT from the Driver stage circuit and the AC signal INPUT of the Driven stage circuit are at the same common reference voltage potential.

Subject to individual circuit design, all or any of the above OPTIMISED ELECTRON STREAM © TECHNOLOGY concepts may be used individually, or in combination, or all together - each offering a specific benefit to enhancing electron flow within the tube or circuit.
2. **OPTIMISED ELECTRON STREAM © TECHNOLOGY: OPTIMISED SCREEN-GRID VOLTAGE AND LOAD**

My **OPTIMISED ULTRA LINEAR ©** page describes a design method for optimising the DC supply voltage and load impedance to the Screen Grids in Tetrodes, Pentodes and Beam Power Tubes for "Ultra-linear", or "Distributed Load" operation.

In order to determine what optimum transformer primary tap ratio to use it is essential to physically determine the actual Screen Grid to Anode physical (linear distance) space ratio, because for general audio class electron tubes the ratio of screen grid to plate voltage will be optimally equal to the physical distance ratio of cathode to screen-grid v cathode to plate.

The same principle for optimisation of tube performance may be applied to conventional operation of Tetrodes, Pentodes and Beam Power Tubes in "Pentode' operation - ie, where the Screen-Grids are supplied from a separate DC source to the Plates.

To optimise the Screen-Grid voltage, first carefully and accurately measure the physical gap spacing between the Cathode, Screen-Grid and Plate.

In most cases this can be easily done without having to destroy a valuable tube. Just measure the spacing between Cathode and Anode and of the grid support pins at the top of the tube. In the case of beam power tubes this may be difficult because there is usually a box-like assembly covering the Plate structure. But a bit of ingenuity should solve the problem.

If it becomes necessary to destroy a tube to examine its internals safety precautions must be observed:

1. Wrap the tube in a strong cloth
2. Place the tube in a vice and squeeze the glass bottle slowly until it implodes
or
3. Gently hit the glass with a hammer at a point not directly over the electrode assembly
4. Carefully remove the broken glass and dispose of safely
5. Carefully cut away the electrodes until the elements can be measured

The "gap" spacing ratio can then be calculated for the particular tube type.

To determine the Optimised Screen-Grid voltage, multiply the Plate voltage by the gap ratio.

It is obvious the Screen-Grid voltage will be substantially less than the Plate voltage - typically in the range 30 to 50 % but usually 40% - so a separate stable supply is essential.

The designer has the option of using:

- a voltage divider network from the Plate Supply (not recommended for hi-fi)
- a stabilised Screen-Grid DC supply derived from the same AC source (power transformer) as the Plate supply (not recommended for hi-fi)
- a separate Screen-Grid DC supply derived from a separate power transformer and full-wave rectifier to the Plate supply (tube rectifier not recommended for hi-fi)
- a separate regulated Screen-Grid DC supply derived from a separate power transformer and full-wave rectifier to the Plate supply (tube rectifier not recommended for hi-fi)

What is most important is for the Screen-Grid DC supply voltage to be reasonably constant between no-signal load and full-signal load conditions (ie well regulated).

This can be effectively achieved by using a separate power transformer of generous rating - ie at least twice the maximum signal DC Screen-Grid current, a full-wave silicon bridge rectifier and humungous filter capacitors in capacitor input to filter configuration - preferably with a low DC resistance filter choke installed too.

For the more theoretical designer some thought could be given to the "Virtual Cathode" concept, which suggests that the portion of
electron stream devoted to the negative bias applied to Grid #1 creates a more negative "Virtual Cathode" in the region of the physical Grid element. This concept however is difficult to assess because so long as the tube is conducting some of the electron stream is continuous between real Cathode and Plate. Maybe only the outer portions of the electron stream are affected by the negative bias and not the entire thickness of stream.

The perfectionist - or those having the necessary equipment - looking for the ultimate optimisation could determine the optimum operating voltage for the Screen-Grids by means of a Signal Generator, Distortion Meter and variable voltage power supply to the Screen-Grids.

The optimised AC load impedance for the Screen-grid will be the ratio of DC Screen-grid volts to Plate volts x Plate load impedance. If the Screen-grid load is provided by a fixed resistor the ratio for a Screen-grid - or set of Screen-grids in one side of a push-pull set, will be the DC voltage ratio x one quarter Plate to Plate load impedance

Note however that if the load is provided by a transformer as in ultra-linear or equivalent mode, the Screen to Screen load impedance will be directly proportional, but the turns ratio will be the square of the DC voltage ratio.

eg If the DC ratio is 40% then the turns ratio for the Screen-grid tap on the output transformer will be 0.4 x 0.4 = 0.16 or 16%


### Recent Research

I am indebted to Rudolf Moers, a distinguished Electrical and Electronics Engineer located in the Netherlands, who has made available for us his wonderful recent scientific investigation into the design theory and practice of Ultra-linear audio amplification.

These papers are posted with permission from Linear Audio www.linearaudio.net and their author Rudolf Moers.

- [Part 1 - Power Point presentation](#)
- [Part 2 - Power Point presentation](#)
- [Parts 1 and 2 combined presentation - pdf format](#)
- [Paper - The Ultra-Linear Power Amplifier: An adventure between triode and pentode - pdf format](#)

The engineering design methods developed by Mr Moers may be used to determine theoretical plate/screen load ratios for ultra-linear operation of power tubes.

3. **OPTIMISED ELECTRON STREAM © TECHNOLOGY:**

   **OPTIMISED SUPPRESSOR-GRID VOLTAGE AND LOAD IN PENTODES**

The **PENTODE** electron tube has an extra grid (Grid #3) installed to suppress the effects of secondary emission, as described in my **SCREEN-GRIDS** page.

![Diagram of pentode](#)

Although few true Pentodes are available for audio power amplifier output stage applications, this section relates to them because they are suitable for use in **OPTIMISED ELECTRON STREAM © TECHNOLOGY** applications.

Manufacturers' tube data sheets generally describe Pentodes as having higher measured distortion than Beam Power Tubes so most audio amplifier designs have focused on the latter types.

In the case of recycled or salvaged tubes from yesteryear, it is evident that by WWII, RF design engineers preferred Beam Power Tubes because of their capability to operate at higher RF frequencies, hence the true Pentode enjoyed only a short claim to fame.

One exception to this is the mighty **803 Pentode**, which found widespread use in submarine and destroyer RF applications because of its ruggedness, stability, reliability and long-life. Of interest is that the 803 pentode has aligned grids, each having a ceramic coating to
limit electron attraction, thereby improving predictability and stability of operation, as well as efficiency.

The 837 Pentode tube is also renown as a very reliable oscillator tube for RF transmitters. The 837 Pentode has a Plate structure similar to that of the famous TT21 and KT88 Beam Power Tubes.

However Pentodes do offer user benefits over Tetrodes and have a place in high-fidelity audio and RF amplifiers - particularly for home constructors who might have a box of useful Pentodes just waiting to be used in a suitable design.

It is a well established tube engineering principle that the current in a tube can be regulated using ANY of the grid elements. For example, in domestic radio receivers, the use of multi-grid tubes such as 6A7, 6A8 and 6L7, each having 5 grids, is a standard application of radio engineering design.

However for audio engineering purposes, three grids appears to be the practical limit - beyond which no appreciable benefit is to be realised. In fact, the beam Power Tube utilises only two grids to control current through the tube.

Using the same applied engineering technology as developed for OPTIMISED ULTRA LINEAR© operation, it is possible and practicable in power tubes fitted with a SUPPRESSOR-GRID having an independent base pin connection, to apply a DC voltage and AC load impedance to the SUPPRESSOR-GRID having the same ratio to Plate voltage and load respectively, as the internal electrode physical gap ratio.

IMPORTANT NOTE 1: It is the case in many of the popular PENTODES that the SUPPRESSOR-GRID is internally connected during manufacture to the CATHODE, so it is not possible to externally access the Suppresser Grid. In this class of tube the manufacturer controls the behaviour of the Suppresser-grid and the user cannot do anything to change that.

IMPORTANT NOTE 2: Tube identification protocols describe and illustrate by base pinout diagrams Beam Power Tubes as "Pentodes". These tubes are essentially Tetrodes that have a beam forming electrode used to both confine the electron stream to a pre-determined width within the tube, and to focus the electron flow onto a particular area of the Plate. They usually have aligned Grids to arrange the electron flow in multiple sheets.

Therefore it is essential to physically examine tubes of interest to determine their actual mechanical construction.

DO NOT RELY ON DESCRIPTIONS OR BASE DIAGRAMS PUBLISHED IN TUBE MANUFACTURERS’ CATALOGUES, MANUALS OR DATA SHEETS.

However those tubes having a separate base pin connection for the SUPPRESSOR-GRID offer the designer the option of applying a suitable DC voltage consistent with the proportional voltage divider effect of the internal electrode gap.

The rules and requirements for an adequately regulated DC power source are the same as described above for the Screen-Grid.

For example, in the Type 803 - 12SW dissipation power transmitting pentode tube - the Suppressor Grid is set at nominally 68% of the Cathode to Anode gap. Therefore the OPTIMISED ELECTRON STREAM© value for the Suppressor Grid DC voltage will be the applied Plate Voltage x 68% - but only up to a value 158% of that permitted by the manufacturer’s rated Screen-Grid Voltage (because in the case of Tube Type 803, the maximum permissible Screen-Grid voltage is nominally 43% of the applied Plate Voltage).

In other words, the maximum applied DC Screen-Grid Voltage and/or Suppressor Grid Voltage for OPTIMISED ELECTRON STREAM© operating conditions will be determined by either the maximum rated Screen Grid or Suppressor Grid voltage - whichever is the lesser.

IMPORTANT:

The SUPPRESSOR GRID (GRID #3) regulates the flow of electrons in the tube in the same way as is the case for Control-grid #1 and Screen-Grid #2.

In conventional "Pentode" configuration, the Suppressor-grid is directly connected to the Cathode either internally by the tube manufacturer or by the user.

Having left the Plate as surplus, randomly travelling electrons, they find their way to the Suppressor-grid, thence diverted to the Cathode to be absorbed back into the electron stream. This arrangement obviously creates a short-circuit in respect of those electrons attracted to the Suppressor-grid.

Thus there is an effective internal or external circuit (as applicable) created between the Suppressor-grid and the Cathode, that diverts some of the electrons back to the Cathode. This current is lost to the output power and therefore reduces efficiency in the output power stage.
In the case of the relationship between the Screen-grid and Plate, most experts suggest that the Plate sees the Screen-grid as the “Cathode”, thus if this is so then the DC potential between Plate and Suppressor Grid will be again determined by the linear distance between them - unless the Suppressor-grid is purposefully connected to the Cathode.

It follows that in an **OPTIMISED ELECTRON STREAM ©** technology amplifier where the Screen-grid DC voltage is around 50% of the Plate voltage, if the applied DC voltage is increased from 0 volts (Cathode potential) to a positive voltage greater than the Screen-grid voltage, then the free electrons deflected from the Plate will still be attracted to the Suppressor-grid because it is still negative to the Plate.

It also follows that because the Suppressor-grid is now positive to the Screen-grid, Plate current will increase - albeit slightly.

Since both Screen-grid and Suppressor grids DC voltages will be fixed, it becomes obvious that to control the electron flow within permissible limits, the negative bias voltage applied to Grid #1 Control Grid will need to be made MORE NEGATIVE.

It is also obvious that to limit the **DC** current flow in Grid #3, and to prevent an AC signal short-circuit at the Suppressor-Grids, it is **essential** to load the Suppressor-grids by installing a Grid-stopper resistor of around 75% of equivalent Plate to Plate push-pull load impedance.

eg for a Plate to Plate load of 8,000 Ohms, the transformer will present a load of 2,000 Ohms to each tube in the push-pull pair. 2,000 Ohms x 75% is 1500 Ohms. This is still a relatively small value so should not present significant voltage drop or regulation issues.

This is an important difference between convention and the **OPTIMISED ELECTRON STREAM ©** configuration.

In a conventional pentode circuit with grounded Cathodes, the Suppressor-grid is directly connected to the Cathode so the Suppressor-grid is fixed at 0 VDC. However in the case of **OPTIMISED ELECTRON STREAM ©** configuration, the Suppressor-grid will be fixed at a relatively high DC voltage set to enable the AC voltage to be aligned with the physical gap in the tube. The circuit design then needs to accommodate this to protect the Suppressor-grid from self-destruction through over-current.

The optimised **AC** load impedance for the Suppressor-grid will be the ratio of DC Suppressor-grid volts to Plate volts x Plate load impedance.

If the Suppressor-grid load is provided by a fixed resistor the ratio for a Suppressor-grid - or set of Suppressor-grids in one side of a push-pull set, will be the DC voltage ratio x one quarter Plate to Plate load impedance.

When used in an **OPTIMISED ULTRA LINEAR ©** configuration as shown above, it will also will be loaded by the tapped primary winding on the output transformer. The **AC** load impedance will be determined by the ratio of the physical gap between the Cathode and Suppressor-grid compared to the Cathode to Plate, as applicable - nominally 75% of the Plate to Plate load.

The Suppressor-grid to Suppressor-grid load impedance will be directly proportional, but the turns ratio will be the square of the DC voltage ratio.

eg If the DC ratio is 75% then the turns ratio for the Suppressor-grid tap on the output transformer will be 0.75 x 0.75 = 0.5625 or 56.25%

Consequently, proportionate audio **POWER** is drawn off from the Screen-grid and Suppressor-grid by the output transformer.

**PENTODE** tubes suitable for high-fidelity audio power output applications using **OPTIMISED ELECTRON STREAM ©** technology include:

- 802
- 803
- 804
- 837

I have not listed the EL34/6CA7, its smaller brother the EL84/6BQ5 and cousin 6M5, because the construction and effect of the Suppressor-grid in these tubes is "nominal" and not in the same league as those of the transmitting tubes listed above. Being manufactured from very fine wire, the Suppressor Grid in these tubes is not be capable of handling significant current or power. For high-powered audio amplifiers superior options are available as shown above.

However the EL34/6CA7, EL84/6BQ5 and 6M5 are suitable for effective use in **OPTIMISED ELECTRON STREAM ©** amplifiers where the Screen-grid is set at 40% of Plate voltage and Suppressor-grid is connected directly to the Cathode in the usual way, and in **OPTIMISED ULTRA LINEAR ©** amplifier designs.

### 3.1 **OPTIMISED ELECTRON STREAM © TECHNOLOGY - SILICON DIODE FEED TO GRID 3**
Consider also **OPTIMISED ELECTRON STREAM © TECHNOLOGY - SILICON DIODE FEED** (as descibed in Section 4 below) to the Suppressor Grid.

In this case, a conventional pentode configured amplifier - where the pentode tube has a separate externally connected independent Grid 3 pin (typically connected to the cathode or ground) - may be modified by installing a silicon diode between the Suppressor-grid pin on the tube socket and Cathode or ground - as applicable. The arrow must point towards ground - ie the marked terminal on the diode to the Suppressor-grid pin.

This configuration allows AC current to flow to ground but blocks DC current into the tube.

If any instability or non-linearity occurs, a 1,000 Ohm resistor may be installed shunting the diode, to create a permanent DC current path to the tube and anchor the Suppressor Grid to the Cathode or ground.

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### 4. OPTIMISED ELECTRON STREAM © TECHNOLOGY: SILICON DIODE FEED

Conventional historic tube amp design using tetrode, pentode, or beam power tubes, evolve about a push-pull output stage configuration typical of the sketch below:

In the example cathode-bias is shown, however the same principles apply for a fixed-bias design.

The notable feature of this design is that everything is symmetrical and so is easy to draw, read and understand.

The configuration of each output tube is considered to be equally distributed about the central axis of the output stage, (being the B+ and centre-tap of the output transformer).

The core electronic design concept assumes (deems) the Plate current in each tube will be identical at all times and therefore any distortion in the plate circuits is cancelled out via the push-pull effect. For an explanation of this refer to the RCA Tube Manuals.

Screen-grids are not considered to be more than a power output/efficiency enhancing benefit derived from tetrodes v triodes, and as shown in the example above, are not connected in any manner other than the most basic available - ie connected together and supplied from the same power source as the Plates.

So in theory, all of the components operate in a synchronous manner such that the output stage is efficient and delivers its power at low distortion.

Unfortunately things are not always as they appear.

The standard tolerance on components is usually around + or - 10%, however some components, including the tubes themselves, are assigned much wider tolerances.

Modern resistors are typically + or - 5% however + or - 10% tolerance is still used.
Modern capacitors display tolerances that vary with construction material and style.

Electrolytic capacitors typically display -20% to 100% on nominal capacitance, thereby affecting gain across the frequency range.

Vacuum tubes offer a tolerance of + or -20% on transconductance when new. Depending upon circuit parameters, performance usually varies downwards with use. If one power tube draws grid current early on then performance of the pair will suffer.

Transformers vary dramatically. Even if the primary centre-tap is exactly in the centre of the total number of turns - ie the number of turns either side of the centre-tap is exactly equal - the transformer may still not deliver an equal power transformation between primary and secondary if the magnetic properties of the two halves of the primary are not identical. Also, if the secondaries are not equally distributed about the primary the induction into each secondary may vary between halves. Factors such as core design and winding design will influence the end result.

And what about the symmetry of the driver stage? This too is subject to tolerance variables and may deliver an unsymmetrical signal drive voltage to the output tubes, resulting in uneven power output from each half.

So what appears to be a perfectly symmetrical design is in fact a widely varying practical configuration.

One obvious variant is Plate-current.

Many of the popular tube types do not deliver a linear response between zero signal conditions and maximum signal conditions. Whilst most guitar amp users would be familiar with the concept of "re-biasing" after changing an output tube, it is not the norm in hi-fi equipment. However despite good intent, guitar amp (and hi-fi amp) users are blissfully unaware that their beautifully balanced output stage at zero signal is nowhere near balanced at maximum signal.

In lower-cost/lower quality transformers it will be found by measurement that the DC resistance of one half of the primary is somewhat different to that of the other half - resulting in uneven Plate voltage as Plate-current increases.

Imbalance in a push-pull output stage results in loss of power and increased distortion.

This condition is more likely in high-gain tubes like the EL34/6CA7, EL36/6CM5, KT88 and 6550.

SCREEN-GIDS

Ideally, the output from the Screen-grids is also identical and therefore cancels out at the output transformer centre-tap.

But note from the above design that any voltage appearing at the centre-tap of the output transformer - whether it be derived from a difference in Plate characteristics, transformer characteristics, untransformed signal, reflected back emf from the loudspeaker, or simply hum as a ripple voltage - will appear on one or the other Screen-grid as either direct injection or feedback.

Obviously Screen-grid current will normally be a portion of (ideally balanced) Cathode-current, but if different brand tubes - or tubes of differing design from the same manufacturer - are used in the output stage pair it is likely that the Screen-grids will behave differently - resulting in not only different tube characteristics across the range but also differences in the Screen-grid performances. Imbalance becomes apparent as distortion.

It follows then that a useful object of amplifier design would be to eliminate the Screen-grid as a variable from the system.

This proposition is very well explained by Renato D. Tancinco of the Phillipines, in his 1961 US Patent 3153766.

In this patent, Tancinco presents his design, which aims to eliminate crossover distortion in tetrodes and pentodes operating in Class B mode - EL34/6CA7 users take note.

Unfortunately this design only works in Class B mode because it cancels out part or whole of the opposite polarity alternating signal in the output stage, however it does offer significant advantage as the patent itself explains.

As noted in my Screen-Grids paper linked above, reference to tube handbooks shows that in a typical beam power tube, the Screen Grid current at maximum signal power is around 20% of Plate current. This ratio of currents appears to be largely independent of Plate voltage. It would therefore be reasonable to assume that up to 20% of prospective signal power is lost in the Screen Grid circuit in a conventional amplifier. (Power = volts x amps. Power supply voltage to the screen-grids can be up to 100% of plate voltage)

(Note: Two notable exceptions are the 807 and 814 beam power tubes that incorporate advanced design technologies to increase tube efficiency and reduce distortion, however in the overall scheme of things this technology appears to have been limited to these two tube types - if you are aware of others please let me know)

Two conventional options present to overcome this nominal ratio of 20% plate Current:

The first is ultra-linear connection, where all the electrons collected by the Screen Grids are fed into the output transformer, but in the process modify the output stage characteristics.

The second is to increase the value of the Screen Grid-stopper resistor to a value sufficiently high to resist the flow of electrons to the
However the Grid-stopper resistor must be non-inductive to prevent oscillation. It must also be capable of handling the Screen current passing through it. One way of doing this is to use parallel carbon composition resistors (not film type - to prevent fire) of sufficient number to obtain the required heat dissipation rating to do the job without excessive temperature rise in the resistors.

A further problem here is regulation of the Screen Grid supply. Obviously a Grid-stopper resistor of say 5,000 - 10,000 ohms will present a significant voltage drop when Screen Grid current flows - if it does.

The loss of regulation may be a price we have to pay to obtain a high standard of performance.

Another and previously unpublished option to creating an operating environment where the Screen Grids will be at a DC potential sufficiently high enough to attract and accelerate electrons towards the Plates but - to maximise power output - not to collect and divert them to earth through the B+ supply, is the humble silicon diode semi-conductor rectifier.

By inserting a standard half-wave silicon rectifier diode in series with the Grid Stopper resistor, an electronic control circuit is created whereby the Screen Grid will be able to be energised at DC potential attracting and accelerating electrons towards the Plate - still electrostatically controlling current flow in the normal way - but blocking the flow of AC current from the Screen Grid back to the DC source - ie "one way traffic"

This works because the current flow in the tube is always from the Cathode to the Anode (Plate). The diode, being a semi-conductor, blocks current flow in the reverse direction, thus enabling DC current to feed it in the conventional manner but blocks AC current from passing back through it to a load.

Thus then there is no circuit formed between the Screen-grid and the load so no current can flow in the usual direction.

This causes the tube to behave very much like a triode, with Plate-current being more or less controlled exclusively by Grid #1.

The diode is connected between the B+ supply (line) and the Screen Grid (load) such that the arrow points towards the Screen Grid. ie forward current is from the line to the load.

This arrangement offers huge benefits, because it prevents the Screen Grids from collecting electrons - thereby diverting all the signal output to the Plates, increasing tube efficiency, reducing distortion and increasing frequency response, as well as eliminating the usual effects on changes in Screen Grid voltage on Plate Current - therefore improving transient response.

One major benefit is that the diode is not in the signal path and therefore does not modify the sound.

A secondary benefit is that there are no bypass or power supply capacitors (eg paper, polyester or electrolytic) in the Screen-Grid signal path, which is a further major improvement.

A further benefit is that the non-linearity described under Fig. 2 above will be less of a problem for us because the Screen-Grid component of the signal (ie those electrons normally collected by the Screen-Grid) is diverted to the Plate.

Thus by inserting the humble silicon semi-conductor diode in the output circuit, we can completely break the bonds of traditional audio practice and take a great leap forward!!

This is not tube heresy, because the diode is not in the signal path - it merely prevents the signal from being affected by adverse circuit parameters such as short-circuited Screen-Grids, fluctuations in Screen-Grid voltage and power supply filter capacitors.

The relatively low reverse resistance of the diode appears to adequately satisfy the need for a low impedance return path to AC earth, so the Screen Grid is not actually isolated from AC earth - but there is sufficient impedance in the circuit to discourage electron flow through it.

Note: Having regard to the EIMAC articles regarding secondary emission in tetrodes referenced above, it should be the case that the use of a silicon diode in the Screen-Grid supply will not impede reverse current flow - provided a suitable bleeder resistor is used between the diode and B+ source - as would be the case without the diode in the circuit.

Some audiophile experimenters have used single or series strings of zener diodes in this kind of circuitry to regulate the DC Screen Grid voltage derived either directly from the Plate or from the B+ supply, however I have used single conventional 1A 1000 PIV silicon rectifiers (from B+ supply only) with good results.

Important Note: When Zener Diodes are inserted in series with the Screen-Grid supply to both drop and control Screen-Grid voltage, they are connected in reverse polarity to the normal rectifier style diode described here, hence their effect on Screen-Grid behaviour and of "sound" is quite different. A real danger with the series Zener Diode configuration is that if the diode breaks down and short-circuits then full supply voltage will be applied directly to the Screen-Grid. This may destroy the tube in the process.

A further (and very effective) enhancement is to use a separate diode for each Screen Grid (or each set in parallel-push-pull) to ensure there is no cross-modulation in the push-pull activity. This places back to back diodes between the Screen Grids, which makes each half of the AC push-pull circuit independent to the other. Less signal averaging and less cross-talk occurs between each
half of the push-pull pair, so the sound is cleaner.

In stereophonic amplifiers using a common power supply, this system provides significantly greater channel separation.

Of course, silicon diodes can be retrofitted to an existing amplifier however the negative feedback loop should be re-calibrated to suit the changed output circuit conditions.

It may be necessary to re-calibrate Grid #1 (Control Grid) bias to ensure Plate Current and Plate Dissipation are optimised within the tube manufacturer's design centre ratings.

In already set-up hi-fi amplifiers, it should not be necessary to change operating conditions because the Plate current is already determined by the Screen-grid voltage and not the Plate voltage - but a prudent owner will check in any case to be sure.

If any reader can shed further light on this breakthrough new concept please email your thoughts.

**Important: Please note this modification is not suited to Class B guitar amplifier applications** (this means most of the "big" guitar amps) because the sound produced by the silicon diode to Screen-Grids configuration is cleaner and less distorted, dynamic range (transient response) is substantially improved and power output is substantially increased - all advantages for hi-fi but not so good for a guitar amp.

This is because many guitarists, in order to attain or emulate a particular "sound" - and thus for them "normal" usage of their guitar amplifier - operate the amplifier into the severe distortion range by simply driving to full output or more. Some operate in the sustained overload range continuously, using reverb, tape echo, electronic echo or acoustic feedback as a musical effect.

In a typical commercial guitar amplifier - particularly those with tube rectifiers - the power supply will collapse and simply run out of puff when overloaded, resulting in substantially reduced B+ supply voltage, lower power output and increased (severe) distortion as the output signal goes into square-wave like response. But the use of silicon diodes changes the tube characteristics insofar as the normal limit on Plate current as controlled by the Screen-Grid is removed, allowing Plate current to increase in proportion with the signal up to a maximum "saturation" point where more drive in does not produce more power out.

Note also that to maximise output power and minimise distortion in a Class B amplifier, it is vitally essential to balance each half of the push-pull pair of tubes to ensure DC current in the output transformer is reasonably equal. **The more tubes in the output stage the harder this is to achieve.**

Unfortunately, most high-power (100 W RMS +) guitar amplifiers do not provide individual grid-bias adjustments for the output tubes. Under such conditions, to achieve balanced DC Plate-current it may be necessary to set Grid 1 bias control voltage at maximum signal - not at quiescent (zero signal) as is popularly expounded, and to mix and match the tubes either side of the output transformer to attain reasonably equal balance in total Plate-current per side. (This may result in some unbalanced DC hum at zero signal).

In an amplifier having a single bias supply it may be also necessary to modify the circuit to install a means for balancing AC signal drive voltage into the output tubes because, as well as being dependent upon primary Grid #1 DC bias voltage, the Plate Current will also be dependent upon AC input volts to Grid #1. Note though that the downside to this is that when a tube is replaced, re-biasing is essential.

For example, I conducted a test with a Marshall Model 1959 100W super-lead amplifier, with 4 x EL34 tubes running at 520 VDC B+.

When silicon diodes were fitted to the Screen-Grids instead of the designed 1000 ohm grid-stopper resistor - one to each Screen-Grid, power output increased from about 90W RMS in OEM configuration to about 160 W RMS with diodes. Screen-grid current was negligible, suggesting the tubes behave like triodes, however Plate current increased to about 180 mA per tube, which increased net plate dissipation at full output to about 55 Watts - a certain recipe for very short tube life considering the EL34 has a rated Plate-dissipation of 25 W.

Plate current then in this situation is primarily controlled by Grid #1 alone.

In this case the amplifier simply gets louder and louder without the usual breakdown signs before clipping, enabling the amplifier to be overdriven continuously to self-destruction. In this particular amplifier, the power transformer is rated at about 250 VA, and a quick calculation will show this component will also have a very short life expectancy with silicon-diodes to the Screen-Grids - but the sound is great!!

**GENERIC CONCEPT CIRCUIT**

A conceptual circuit using the Type 803 Power pentode Tube in an OPTIMISED ELECTRON STREAM © TECHNOLOGY design as described above, is illustrated below:
This circuit is generic to all 3 Grid power pentodes.

For **Tetrodes** and **Beam Power Tubes** just delete the Grid #3 output transformer transformer tap, and its separate Grid #3 DC supply - a Tetrode or Beam Power Tube will have only a Grid 2 in the circuit.

Note: Westinghouse declared the following in their June 1941 user instruction sheet supplied with each 803 tube:
Note the reference to "Tetrode" connection and its effects.

This design feature offers a range of options to the DIY designer/constructor.

Important Note: In the case of a Beam Power Tube, the beam forming plates in a Beam Power Tube are not normally connected to an active circuit element - ie are usually internally connected within the tube to its own Cathode by the tube manufacturer. If available as a separate connection, they should be externally connected to the Cathode in the usual way.

Note: If a voltage measurement is taken either side of the silicon diode in an ultra-linear configuration circuit - ie on the screen-grid side and on the transformer side - obviously a reading will be evident. The reading on one side will be out of phase with the reading on the other side. DC current through the diode can be measured by inserting a small resistor (10 ohms) in series with the diode on the supply side and reading the current through the resistor.

4. OPTIMISED ELECTRON STREAM © TECHNOLOGY:
   PLATE, SCREEN-GRID (GRID #2), SUPPRESSOR-GRID (GRID #3) and CATHODE AC CIRCUIT BYPASS CAPACITOR

4.1 OPTIMISED ELECTRON STREAM © TECHNOLOGY:
   BYPASS CAPACITOR CONSTRUCTION AND INSTALLATION

4.1.1 Non-polarised Bypass Capacitor

Irrespective of choice of Screen-Grid and Suppressor-Grid DC supply method, to obtain the full benefit from the application of OPTIMISED ELECTRON STREAM © TECHNOLOGY in Tetrode, Pentode and Beam Power Tube wide-band amplifiers, it is absolutely essential to bypass (or wholly replace) the final polarised electrolytic capacitor in ALL of the B+ Plate AND Screen Grid AND Suppressor Grid supplies, with a suitable non-polarised high quality mica, polyester, polypropylene or oil-filled paper etc. capacitor, having a suitable value (of say 10 to 100 uF for audio), to provide an efficient and stable AC bypass at all signal frequencies and under all operating conditions.

The reason for the use of a non-polarised capacitor is simply that polarised electrolytic capacitors offer asymmetrical impedance to the current flow - depending upon the direction of the current through the capacitor. Most importantly for high-fidelity reproduction, polarised capacitors offer asymmetrical characteristics to forward or reverse AC current. This is evidenced by the widespread use of polarised capacitors in loudspeaker crossover networks (which are purely AC) - even in the cheapest commercial speaker systems.

The reason for the relatively large value of capacitor suggested is that it is in series with the load on the Plate and Grids, forming an
LC or RC (depending upon the output stage configuration) series network. If the value of C is low then peaks or resonance can occur in the audio range - particularly in the mid to high frequency band where harmonics are present.

This capacitor serves to effectively AC short-circuit (or bypass) the DC power supply and thus eliminate the power supply and its components from the AC signal path, and to ensure that any shortcomings in polarised electrolytic capacitor performance are eliminated - but in such a way that the signal is not significantly aurally affected.

In the case of the Plate circuit of Triode, Tetrode, Pentode, Beam Power Tube and Ultra-linear wide-band amplifiers, the non-polarised capacitor should be installed at the centre-tap of the output transformer.

In the case of amplifiers having separate Plate, Screen-grid and Suppressor-grid DC power supplies this requirement also applies to each of the Screen-grid and Suppressor-grid DC circuits as applicable.

To ensure adequate low frequency response each of the separate circuits must have as large a value as is practicable.

A 400 VAC (560 VDCW) Motor Start Capacitor is ideal for this function and they are readily available in non-polarised polypropylene construction. The voltage rating must be adequate to handle the sum of the B+ DC voltage plus the AC rms signal output voltage.

I would recommend a parallel connected non-polarised capacitor arrangement, to provide 100 to 200 uF total. For higher B+ voltages the capacitors can be connected in series (800 VAC 1120 VDCW), noting that when seriesed, the effective capacitance is halved.

A further refinement is to apply the "Rule of Hundredth's", which says that instead of using a single capacitor - eg a large electrolytic, a bank of capacitors is installed. Each capacitor is one hundredth the value of its adjoining capacitor. For example, instead of installing one single 100 uF electrolytic, install a 100 uF, 1 uF, 0.01 uF, 0.0001 uF etc. wired in parallel. Lead length of the smaller capacitors must be kept as short as possible to prevent stray capacitance or inductance. It is also important to ensure all capacitors installed are capable of coping with the applied voltages without stress.

Of course the bypass capacitor is installed on the line (source) side of the Screen-Grid-stopper resistor and/or diode, as the case may be.

Note: This method may result in resonances in the audio range, particularly to harmonics, resulting in sibilant accentuation and "hissy" voice. It is thus not suitable in all amplifiers.

Note 1: Please note that the irrespective of the value of the electrolytic filter caps - even to many thousands of uF - the value of the non-polarised cap is still critical in relation to tone, or spectral balance, across the audio range. To optimise tone experimentation is essential.

Note 2: Modern "fast" capacitors have a different tone to older oil-filled types. It may be necessary to use oil-filled paper caps to obtain a smoother, less harsh tone. It all depends upon the circuit design and componentry used. There is no definitive answer. Unfortunately the older oil-filled paper caps are physically larger so need more chassis space. They also do not usually come with flying leads, which makes wiring more difficult because the terminal lugs are exposed. Ensure voltage rating is adequate.

4.1.2 Electrolytic Bypass Capacitors to B+ Supply

Please note that as explained in my Power Supplies page, notwithstanding the obvious benefits from the use of non-polarised capacitors as described above, it remains essential to good transient response to install large values of electrolytic capacitors to store adequate power to satisfy the demands for transient peak signals.

The question is "how big a value"?

In the case of power requirements, full particulars are provided in my Power Supplies page.

But what about "sound"?

It has been demonstrated by early amplifier designs produced in the 1940's and 1950's that the frequency response - even in the highest quality equipment, tended to roll-off at both high and low frequencies.

Frequency response usually deteriorated as power output increased. This was an attribute ("power response") not usually presented in the glossy sales brochures.

Modern digital recording techniques and playback media have dramatically increased both low and high-frequency response for the typical recording, challenging even the very best of tube audio amplifier designs - particularly when played at high-volume.

But all is not lost!!

Modern capacitors offer improved performance and reliability over their ancestors. They are also available in values unheard of in the days of tube rectifiers. (eg 32 uF was "large" in the 1950's but now 100,000 uF is "medium.")

The thin film caps of today charge and discharge much faster, enabling larger values to be used in common applications where large values were previously forbidden - such as interstage coupling caps.
Modern capacitors offer reduced unwanted side effects, such as inductance, leakage and resonance, so offer improved high-frequency performance and audio clarity.

One effect of this is a reduction in the level of negative loop feedback needed to offset rolloff in frequency response of an amplifier - a definite advantage.

In the case of low frequency performance we can retrospectively improve old designs by using higher values of filter bypass capacitors.

Since the bypass capacitor forms the return AC circuit for each stage in the amplifier, it follows that the impedance of the bypass (filter) capacitor at any given frequency will be a portion of the total impedance of the circuit being bypassed. Now since the impedance of a capacitor varies in direct proportion with the value of capacitance at any given frequency, it follows that providing we reduce the value of the capacitor's impedance to a value that has minimal effect upon the circuit, then we can attain improved performance from the circuit.

Another way of explaining the concept is that traditional tube electronic design engineering principles assume that the B+ rail is at AZ zero (or earth) potential - regardless of the applied DC voltage.

This is a practical approach for many applications, but ignores the reality that capacitors - particularly those of the electrolytic variety - have their own characteristics, which are injected into the circuit and therefore MUST influence the sound we hear.

Since the capacitive reactance of a 25 uF capacitor at 30 Hz is nominally only 212 Ohms, it suggests that the influence of the capacitor may be negligible. However if the inductance of the capacitor is only 0.1H then the inductive reactance in the capacitor is 3140 Ohms at 5 kHz - and more at higher frequencies.

So we can see that increasing capacitive reactance will decrease low frequency performance and decreasing capacitor induced inductive reactance will increase high-frequency performance.

Since measured inductance and capacitance values from typical large capacitors - eg above 500 uF - do not appear to display the characteristics experienced aurally there may be an alternative explanation. It may be that the bypass capacitor forms an RC or LC series network with the plate resistor and/or output transformer, forming a bass boost circuit. This is easier to see with the output transformer, where either one end (in the case of a single-ended output stage) or the centre-tap (in a push-pull output stage) forms the terminal at which the output is taken off. but in the case of driver stage it would seem the series decoupling resistor causes the formation of the RC network that creates the bass boost effect.

Either way it is desirable to tune the network to the preferred frequency - eg 40 Hz

The question is what is the magic number?? How big to we need to go??

To attain extremely good low-frequency response, from practical experimentation I would suggest the minimum value of the bypass capacitor for any stage in an amplifier or pre-amplifier, including the output power stage, may be calculated by dividing the constant 15,000,000 (15 million) by the value of the plate load resistor (or cathode-follower cathode load resistor) for that stage.

This approach will produce values of 150 uF for a 100k plate resistor and 2,250 uF for a 6,600 Ohms Plate to Plate output stage.

If those values appear frightening, then try a lesser constant - say 10,000,000

If the B+ supply supplies more than one stage or, in the case of some phase-splitters having more than one plate resistor, then the value of the resistor should be calculated as the average of all the resistors in the circuit.

If the B+ supply supplies a stereo pair of amplifiers then the value of the plate load resistor used to calculate should be half of the single channel value - ie each bypass capacitor should be twice the size as for a single channel.

If the output stage uses more than one pair of tubes from a single transformer, then use the transformer actual nominal rated load impedance - not the effective impedance as seen by each pair.

It will be noticed that these values of capacitance are substantially higher than convention, however this is what I have determined from extensive critical listening tests.

The general object of this design approach is to introduce a circuit resonance induced tonal characteristic that is pleasing.

Too high a value of capacitor will deliver undefined bass, so some tweaking may be necessary.

It is desirable for all stages to have the same tonal characteristic, so this formula assists to achieve that. In other words, each stage should ideally have proportionately the same tonal or frequency characteristic.

Note 1: This "rule of thumb" formula deals only with tonal characteristics - power (energy) requirements for the output stage are not covered by this. However it is easily seen that the values produced by this design approach will supply adequate power for most applications.
Note 2: Regardless of the value of electrolytic capacitors used for bypassing and filtering, non-polarised bypass capacitors are still essential for good high-frequency performance and low intermodulation distortion.

Note 3: In the case of guitar amplifiers the above formula is not applicable because the lowest frequency to be reproduced is about 80 Hz. In this case a constant of say 10,000,000 or less would be appropriate.

Note 4: In the case of bass guitar amplifiers, where the lowest frequency to be reproduced is around 40 Hz, then for outstanding results the constant needs to be in the region of 20,000,000. This value of capacitance will also deliver adequate power to the output stage.

Note 4: Large values of capacitor can be lethal, so discharge resistors should be installed as per instructions provided in my Power Supplies page.

Note 5: In my experience, larger bypass capacitors have the effect of improving circuit stability and improving high-frequency audio performance.

4.2 OPTIMISED ELECTRON STREAM © TECHNOLOGY:
RATIO OF SCREEN-GRID AND SUPPRESSOR-GRID BYPASS TO PLATE BYPASS CAPACITORS

4.2.1 Introduction

Since the advent of Tetrodes and Pentodes, it has been standard practice to install a small bypass capacitor from the Screen-grid to ground (Cathode) in Tetrodes and Pentodes used in voltage amplifier stages.

This is shown as C2 in the figure below.

![Circuit Diagram]

The purpose of the bypass capacitor is to reduce Grid to Plate capacitance, remove undesirable audio and high-frequency signals such as RF components from the output before the load, and to improve the decoupling and stability of the stage.

In voltage amplifier (driver) stages the value of this capacitor has historically been in the order of 0.1 to 0.5 μF, the latter value being considered by Radio Engineers to be adequate for good quality audio purposes. A similar situation exists in RF power amplifier stages.

It should be noted though, that this value of capacitor is usually associated with small tubes in high-impedance circuits, such as the EF86, 6AU6, 6U8, 7199 etc, where the value of Screen-grid supply resistor may be in the range 100k to 1 Meg Ohms with very low Screen-grid current.

An example is shown in the Mullard High-fidelity Pre-amplifier.

4.2.2 Theory

For the theoretically minded, the formula for calculating the value of the bypass capacitor in a voltage amplifier stage is given courtesy of the Radiotron Designers Handbook, 3rd Edition (1940).

4.2.3 High-fidelity Audio POWER AMPLIFIER Applications

Notwithstanding the above historic convention, in high-fidelity audio POWER AMPLIFIER output stages a very different situation applies.
If we think for a moment, it can be easily seen that there is both a DC and an AC signal path from the negative terminal of the bypass capacitor up through the capacitor to the Screen-grid external to the tube, thence from the Screen-grid to the Plate inside the tube. The latter will be the case (even if we do not want it) because the Screen-grid is negative to the Plate.

As explained above, the portion of Screen-grid current in a power tube can be quite high - depending upon output stage configuration and applied voltages to the Screen-grid and Plate respectively.

Since the internal impedance of the bypass capacitor will be relatively small and the Screen-grid is operating independently of Control Grid #1, it follows that the magnitude of the current flowing from Screen-grid to Plate will depend more or less entirely upon the actual applied DC voltage between Screen-grid and Plate and the value of the Plate load - which will be also seen by this secondary circuit. That is "secondary" to the primary Cathode to Plate circuit.

Obviously, the higher the difference between actual applied DC voltage between Screen-grid and Plate, the more current will flow.

In Tetrode and Pentode and Beam Power Tube applications where the Plate and Screen-grid operate at the same DC voltage, including Triode and Ultra-linear connections, in the conventional and very common configuration shown above, it is suggested by most writers that the Plate will function as the primary anode so long as the Plate signal voltage does not drop below the DC Screen-grid voltage. In this case, tube manuals show that about 10-20% of Cathode current is lost in the Screen-grid circuit.

Since the bypass capacitor C1 is common to both Plate and screen-grid circuits, in terms of frequency response and dynamic response whatever happens in one will happen in the other.

But when the DC Screen-grid voltage is less than the Plate voltage - as in RF linear amplifiers, transmitter modulator amplifiers, transmitting tube audio amplifiers, Public Address amplifiers or OPTIMISED ELECTRON STREAM © TECHNOLOGY applications as shown in the following diagram - then current MUST flow between Screen-grid and Plate.

This is because a secondary DC and AC circuit is established between Screen-grid and Plate, with the Screen-grid forming the negative terminal/element.

In high-voltage amplifier designs, the voltage between Screen-grid and Plate may be in the order of several kilovolts (kV).
limiting factors to current flow in this secondary circuit will be the Plate load impedance for AC current (the DC resistance of the output transformer is negligible) and the value of the Screen-grid resistor if used (either voltage dropping resistor or grid-stopper) for both AC and DC current.

For explanatory purposes, the internal tube resistance between Screen-grid and Plate may be assumed to be zero.

It follows then that the Cathode to Screen to Plate secondary AC circuit is in parallel with the Cathode to Plate primary AC circuit.

As explained above, the value of Screen-grid current - and therefore its contribution to audio power output, can be significant.

Since the current in both circuits combine together in the negative to positive Screen-grid to Plate section of the circuit inside the tube (and thence common return to the Cathode via the B+ filter capacitor at the output transformer centre-tap) it follows that any difference in the audio signal between primary and secondary circuits will be apparent at the output transformer.

For example, if the Screen-grid bypass capacitor is too small, that portion of audio power output contributed to by the Screen-grid secondary circuit as described herein, will not have the same low-frequency response as the primary Plate circuit and therefore low-frequency power output will be proportionately reduced.

For example, in the Mullard High-fidelity Pre-amplifier circuit, typical of conventional design, the Screen-grid bypass capacitors C9 is 80 times the value of C8, and C17 is 160 times the value of C12.

The value of the Screen-grid bypass capacitor will also affect the operation of the Plate circuit B+ bypass capacitor, because the B+ Screen bypass cap and B+ Plate bypass cap are in series in the signal circuit.

Hence it may be deduced that:

Where a separate Screen-grid power supply is provided, it is most important for full-power hi-fi reproduction at very low frequencies, and for signal balance within the tube, to ensure the value of the final Screen-grid B+ bypass filter cap is not less than the value of the Plate circuit B+ bypass filter cap.

In the above diagram the Plate bypass capacitor is shown as C1 and the Screen-grid bypass Capacitor as C2.

Note: Even though the installation of a voltage dropping resistor or grid-stopper resistor to the Screen-grid (R3 in the voltage amplifier circuit diagram above) may reduce AC and DC current, the issue of AC impedance remains - hence the grid resistor may be disregarded for this aspect of hi-fi design.

It will be readily seen that in a power output stage where the Plate and Screen-grid share a common AC circuit return at the power supply, and regardless of the use of a grid-stopper or dropping resistor (R3 in the above diagram) or not, the above argument does not apply because both Plate and Screen-grid will share a common B+ bypass capacitor.

BUT - where the screen-grid is supplied through a filter choke from the centre-tap of the output transformer at C1, and bypassed by its own electrolytic capacitor C2, the configuration shown above is still is applicable.

However bear in mind that the regulation of Screen-grid voltage is also extremely important so a separate supply should remain an essential design element.

The above comments also apply to the Supressor-grid

4.2.4 Cathode Bypass Capacitor

In the case of Tetrode or Pentode amplifier output stages having Cathode Bias, it is usual to instal a Cathode-bypass Capacitor as shown in the following diagramme:
It can be readily seen from the way the circuit is drawn that the Cathode-bypass Capacitor is in series with the B+ Plate and Screen-grid supply.

It follows that if the Cathode-bypass capacitor is too small, that portion of audio frequency response determined by the Cathode circuit will not have the same low-frequency response as the primary Plate circuit and therefore low-frequency power output will be proportionately reduced.

From the above explanations it can be demonstrated that the value of C3 must be at least equal to the value of C1.

The more theoretically minded can calculate the actual values needed for equilibrium in the frequency response characteristics for each part of the circuit.

Where a separate Screen-grid power supply is used, as shown below,

it can be readily seen that the Plate and Screen-grid bypass capacitors C1 and C2 are in AC parallel but the set of both is in series with the cathode bypass capacitor C3.

Hence it is also essential that the nominal capacitance value of C3 is equal to the SUM of C1 + C2.
Where separate Cathode-bypass capacitors are used to each Cathode, the above rule still applies for each capacitor.

It is usual for Class A amplifiers to use a single common cathode resistor and no bypass capacitor per push-pull pair of tubes - this is obviously more AC linear.

### 4.2.5 Power Factor

The maximum ideal values for C1 and C2 and C3 can be in the region of up to 5,000 uF per push-pull pair of tubes - see warning re risk of electrocution.

To maintain **OPTIMISED ELECTRON STREAM © TECHNOLOGY** design standards in the output stage circuit, some circuit tuning is essential to optimise the "POWER FACTOR" in the output stage circuit.

In terms of "sound", this is a very critical issue.

This extra step is needed to tune resonances in the output stage circuit to match the characteristics of the output tubes, output transformer and loudspeakers to the signal "sound" or "tone" and listening room acoustics. Too low a resonance may result in a "dull" or "flat" bass sound. Too high a resonance may result in "bass boom" and loss of definition.

To optimise the output stage circuit and deliver maximum power from minimum output impedance with maximum loudspeaker damping characteristics, changes in power factor produced by the inductive reactance in the output transformer will ideally be cancelled out by the capacitive reactance in C1.

To optimise the value of C1 some degree of practical "trial and error" experimentation is needed - a frustrating experience but one worth the effort.

Note C2 and C3 need to be suitably modified as described above and hereunder to maintain the correct ratio to C1 - ie the same capacitance value.

Note also that to overcome non-linearity in the AC bypass circuit, C1 and C2 may need to be bypassed by a small stabilising capacitor in the region of 0.5 uF - but since this small capacitor will directly affect the high-frequency response, it too must be chosen with care regarding both size and material of construction.

**IMPORTANT:**

All of the Plate Circuit output stage power passes through the AC circuit formed by the output transformer and C1 - and whatever else shunts C1.

Since L1 is directly connected to the Power Supply, it follows that the Power Supply is in series with L1 and shunts C1.

This is illustrated in the diagram below:
So to minimise the effects of the Power Supply rectification and filter circuitry on "sound", the value of L1 should be as large as can be practicably sustained - noting that the DC resistance of L1 will directly reduce the available B+ voltage to the Plates.

The larger L1 is, the more AC current will be forced through C1 and less through L1 and associated circuitry.

Another way of expressing this is to say that whatever AC power is lost into L1 and its associated source bypass components - all of which shunt C1 - the less linear the output stage will be at low frequencies.

An inductance of about 10 Henries (minimum) is desirable for L1.

This also holds true for simple one stage filter choke systems, because the rectifier/filter is always shunting C1 - thus will always affect its performance and effect on "sound".

IMPORTANT: To prevent instability in the power supply (which dramatically affects audio sound as heard through the loudspeaker) it is desirable to ensure C2/L1 and C3/L2 are of equal value. Where only C2/L1 are used then it is desirable that C1 and C2 are of equal value. It is thus obvious that a three stage filter enables a higher value of C1 than for a two stage filter.

This point will be expanded in future revisions of this page.

4.2.6 Silicon Diode Feed

When silicon diodes are installed in the Screen-grid and Suppressor-grid circuit when using my OPTIMISED ELECTRON STREAM © TECHNOLOGY design, the above bypass requirements still apply because although the diode will block AC from passing from the Cathode to the Screen-grid and Suppressor-grid internally, it cannot stop the current flow in the external secondary circuit described herein.

4.2.7 Voltage Doubler Power Supply

Where the Screen-grid B+ supply is taken from the output of a voltage doubler rectifier, it may be the case that for convenience the Screen-grid supply is taken from the mid-point of the two series-connected filter capacitors.

However if we analyse the effect of this arrangement having regard to the above, it is easy to see that the external Screen-grid bypass current is passing from negative to positive through the lower filter capacitor.
It is also easy to see that return external Screen-grid bypass current is passing from positive to negative through the lower filter capacitor. Consequently, it is evident that the two currents will cancel out.

Bad move!!

So in other words, this configuration is not desirable for high-fidelity reproduction, even though it may appear to work satisfactorily in public address amplifiers.

There is also an issue of the effect of differences in capacitor characteristics in the forward and reverse directions, as well as the effects of distortion caused by the output transformer.

There is also the issue of excessive ripple in the DC supply.

One solution to both issues may be to install a 60 mA filter choke in the line (supply) side of the Screen-grid B+, then add a second filter capacitor to the Screen-grid B+ at the load side, to provide a separate path for forward and reverse currents.

The value of the second (final) bypass capacitor should be equal to or greater than the value of the seriesed pair.

4.2.8 Capacitive Voltage Dividers

Where the Screen-grid B+ supply is taken from the centre-point of a pair of series-connected electrolytic capacitors in the Plate B+ circuit, the same problems arise as explained above.

4.3 OPTIMISED ELECTRON STREAM © TECHNOLOGY: SCREEN-GRID AND SUPPRESSOR-GRID BYPASS CAPACITOR SIZE:

In the case of OPTIMISED ELECTRON STREAM © TECHNOLOGY where a separate Screen-grid and Suppressor-grid power supply is provided, for full-power hi-fi reproduction at very low frequencies it is essential to ensure the value of the final Screen-grid B+ bypass filter cap (and Suppressor-grid in the case of a Pentode) is NOT LESS THAN the total effective value of the sum of all Plate circuit B+ bypass filter capacitors directly connected to the centre-tap of the output transformer - polarised and/or non-polarised.

Where Cathode-bias is employed, in addition to the above it is also essential to ensure the value of the Cathode-bypass capacitor(s) is not less than the value of the Plate and screen-grid supply capacitors

Note: Where one or more filter chokes are used in the B+ supply, the value of capacitors before the choke(s) may be ignored for this requirement.

4.4 NEGATIVE LOOP FEEDBACK

Where negative loop feedback is used from the loudspeaker terminals back to an early voltage amplifying stage, it can be seen from the above that any defects in performance in the output stage will simply be transferred back to the input, with the result that the amplifier will always be in a constant state of correcting itself.

Hence any use of negative loop feedback should be deferred until the output stage is optimised according to the requirements of my OPTIMISED ELECTRON STREAM © TECHNOLOGY

Please refer to my SCREEN-GRIDS page for full particulars of this requirement.

5. OPTIMISED ELECTRON STREAM © TECHNOLOGY: CONTROL GRID (GRID #1) AC CIRCUIT BYPASS CAPACITOR

In output stages of audio amplifiers it is common to use FIXED BIAS or BACK BIAS to apply and control the Grid #1 - Control Grid bias voltage in the output tubes.

Designers always consider the requirements for direct current operating conditions but often ignore requirements for alternating current conditions - ie signal voltage.

The Grid #1 Resistor to each output power tube forms part of the load for the preceding driver stage. Hence for maximum efficiency and stability, the return path from the output of the driver stage circuit back to its Cathodes should be direct and have very low
5.1 OPTIMISED ELECTRON STREAM © TECHNOLOGY Principles

Bias, by definition, requires a voltage potential to be present between the Control Grid and the Cathode.

CATHODE BIAS usually results in the Control Grid being at nominally 0 VDC and the Cathode at the required bias voltage being + VDC.

FIXED BIAS usually results in the Control Grid being set at the required bias voltage being - VDC and the Cathode at nominally 0 VDC. In the case of FIXED BIAS it is essential to bridge the difference between the central axis of the AC signal input and the power tube Cathodes, such that the central axis is at the same AC voltage as the power tube Cathodes.

It is essential for stable high fidelity operation to ensure that:

a) the Grid #1 circuit has a reliable and predictable low-impedance return path for the AC signal voltage from the preceding stage
b) the Grid #1 circuit has a reliable and predictable low-resistance return path for the DC bias voltage between Grid #1 and the Cathode of the same tube.
c) in a balanced driver stage for Classes AB, AB1, AB2 and B, where the power tubes are biased towards cut-off and driver stage output signal voltages are symmetrically balanced about a virtual central axis having a nominal potential of 0 VAC, it is imperative to ensure the junction of the two Control Grid resistors of the output tubes be AC grounded to 0 VAC.

Thus in an RC (resistor/capacitor) coupled amplifier, it is a fundamental requirement that the Grid #1 Resistor to each power tube provides a return circuit path to the Cathode of BOTH the preceding driver tube AND the power tube to which it is connected.

This is usually, but not always, through the earth or ground terminal of both AC and DC applied circuits.

Fortunately, in most amplifiers using FIXED BIAS or BACK BIAS, the Cathodes of the output tubes are directly earthed (to the chassis), thereby providing a convenient return circuit at 0 VAC potential.

5.2 Cathode Bias

In most amplifiers using CATHODE BIAS, the Cathodes of the driver tubes are earthed either through a bypassed or unbypassed Cathode resistor, hence the Cathode terminal is indirectly AC earthed to complete the return circuit for the driver tube(s).

This principle applies particularly to CATHODE BIASING of power tubes, where the Cathode terminals may well be at say +50 VDC but simultaneously at 0 VAC. (An exception is where the output stage is in Class A and the common cathode resistor is unbypassed to develop negative current feedback in the Cathode circuit.)

![Typical Ultra-linear output stage configuration with CATHODE BIAS. Note the bypass capacitor on the common Cathode resistor, thereby providing a low-impedance AC path to ground.](image-url)
Typical Triode-connected Pentode output stage configuration with adjustable CATHODE BIAS. Note the absence of a bypass capacitor on the common Cathode resistor.

This circuit features + or - adjustment of common bias voltage and also fine adjustment of balance between the tubes.

5.3 Fixed Bias Adjustment

It is common practice in FIXED BIAS amplifiers to incorporate an adjustable bias control circuit, incorporating an adjustable resistive network to enable precision adjustment to the Control Grid voltage and/or Plate Current of the output power tubes.

Typically, this negative polarity DC voltage is sourced from a half-wave or full-wave tube or solid-state rectifier, filtered by a simple resistor/capacitor network.
5.4 Bypass Capacitor Material

In commercial amplifiers with FIXED BIAS, to minimise cost the bypass capacitor is nearly always of the polarised electrolytic variety, but this means that the AC return circuit is not symmetrical. (Electrolytic capacitors have different characteristics in positive and negative polarity circuits).

Consequently, to ensure symmetrical AC circuit configuration it is essential to instal a suitable non-polarised bypass capacitor into the circuit at a point closest to the Grid #1 of the output tubes as is practicable.

Typically this will be at the junction of the two (or more) Grid Resistors.
If a driver transformer is used, and its centre-tapped secondary is not directly connected to the power tube Cathode circuit, then install the bypass capacitor between the centre tap of the secondary and earth.

It is therefore absolutely essential to bypass (or wholly replace) the final polarised electrolytic capacitor, with a suitable non-polarised high quality mica, polyester, polypropylene, paper or oil-filled paper capacitor, having a suitable value (of say 1.0 uF or a 10 uF or more motor start capacitor as above for audio), to provide an AC bypass at all signal frequencies and under all operating conditions.

This small capacitor serves to effectively short-circuit (shunt or bypass) the DC power supply and thus eliminate the power supply and its components from the AC signal path of both the driver tube and power output tubes, to ensure that any shortcomings in polarised electrolytic capacitor performance are compensated - but in such a way that the signal is not significantly aurally affected.

Importantly, it also provides an automatic safeguard against the adverse effects of poorly contacting bias potentiometers and/or adjustable wire-wound resistors.

Normally, the value of the bias supply capacitor will not exceed 10 uF (to ensure fast charging to full bias voltage before the output tubes heat up and commence to conduct Cathode Current) so an extra one or two uF will not significantly affect the charging circuit performance.

If preferred, to achieve the same end result as described above, the final Control-grid power supply filter polarised electrolytic capacitor (and the first as well if so inclined) can be wholly replaced with a polyester or paper or motor start capacitor of say 8 uF value and having a suitable DC voltage rating.

Suitable capacitors may also be reclaimed from unwanted fluorescent lamp-holder assemblies.

For the ultra-fastidious, the "Rule of Hundredth's" may also be applied.

Note: There is no practical limit as to the value of the bypass capacitor, provided the bias supply is capable of charging it quickly to ensure bias voltage is present when the power tubes warm up and commence conducting. I have successfully used values around 100,000 uF, shunted by suitable non-polarised polypropylene caps.

6. **OPTIMISED ELECTRON STREAM © TECHNOLOGY: DECOUPLING OF THE POWER AMPLIFIER FROM THE POWER SUPPLY BY MEANS OF A SERIES CONNECTED SILICON DIODE**

The conventional B+ supply looks something like the following diagram:

![Diagram](image)

It is explained above why Filter Capacitor C1 forms a vital part of the AC circuit in the output stage.

It is also explained why it is desirable to "optimise" the value of C1.

Further, it is explained that the Power Supply is connected in parallel with C1 and therefore also forms part of the AC circuit of the output stage.
Consequently, it can be easily demonstrated that the "sound" of the amplifier will be directly affected - maybe adversely - by the characteristics of the Power Supply.

Since the object of OPTIMISED ELECTRON STREAM © TECHNOLOGY is to "optimise" both the performance and sound of the amplifier, it follows that if the Power Supply can be isolated, or decoupled, from the power stage then a positive benefit might result.

This object may be easily and economically realised by installing a series connected silicon diode rectifier into the B+ supply - having its arrow pointing towards the load - between the Power Supply output terminals and C1 - ie AFTER the Power Supply and BEFORE C1.

Note that C1 must always remain part of the Amplifier, because it forms a direct path in the AC output circuit.

So regardless of whether the Power Supply is of the simple centre-tapped full-wave or full-wave bridge rectifier or full-wave voltage doubler rectifier, or it has a capacitor filter, choke filter or some other combination of filter - or even includes a voltage stabiliser or regulator - to ensure the OPTIMISED VALUE OF C1 is not altered by shunting the Power Supply circuit, significant improvement to performance can be made by installing a series silicon rectifier diode as described.

To ensure cool operation and reliability, the current rating of the rectifier should be generous in relation to the power requirements of the amplifier - eg 3A or 6A. The rectifier can be of the same specification as that used in the Power Supply B+.

Where a separate Screen-grid Power Supply is used, then the same principles apply to C2.
Where an inductor - such as L1 above - is used in the Power Supply, it is preferable for the diode to be installed after the inductor - to ensure the Power Supply is completely isolated from the amplifier.

This method makes it easier to adjust the tonal balance or "tone" of the amplifier power stage - because fewer components are now in the signal path - therefore there are fewer interactive variables to deal with when changing component values.

The same principle apply to L1 and C2.

It will be seen for the above that in the case of simple filters having just one capacitor after the rectifier - and nothing else - the requirement described is met. Unfortunately that simple configuration results in significant hum and ripple and poor quality direct current (DC) - so is not recommended for high-fidelity amplifiers.

7. OPTIMISED ELECTRON STREAM © TECHNOLOGY:
DECOUPLING OF EACH STAGE OF THE VOLTAGE/POWER AMPLIFIER FROM ITS NEXT-FOLLOWING ADJOINING STAGE BY MEANS OF A SERIES CONNECTED SILICON DIODE

Having described how decoupling of the amplifier from its power source facilitates and enhances performance, it follows that the same principles apply to driver stages.

In a conventional amplifier, the stages are connected in a "cascade" configuration.

That is to say, each stage "cascades" into the next - just as a stream "cascades" over its riffles as it runs down a slope.

Conventional theory says that up to three stages may be connected to the same B+ supply before instability becomes a problem.

However:

For optimum performance each stage should be a self-contained discrete circuit - wholly independent from those before and those after.

The usual method of decoupling is to instal a series resistor into the B+ supply between stages. But this produces significant voltage drop when all or any tubes draw current over the steady state condition.

This convention also allows signal from one stage being conducted to an adjoining stage when there is a signal voltage difference between those stages.

So to produce effective decoupling between stages and to prevent each stage sharing the bypass capacitors and associated circuitry installed in adjoining stages - before or after - it is essential to decouple effectively and completely.

To understand the OPTIMISED ELECTRON STREAM © TECHNOLOGY: SERIES DIODE DECOUPLING concept first we need to consider the amplifier as a "system"

A "system" is defines as a series of "processes", each having an input and an output. The ideal system is self-adjusting or self-correcting, by means of a feedback loop (s).

It follows that in such a system what happens in one part also happens in others.
In the case of an amplifier, the signal is present on the B+ rail at each individual stage. In some cases the signal is in phase with other stages, and in other cases the signal is out of phase with other stages.

Therefore the B+ rail is common to all stages. Looking at it another way (ie from the B+ line), the B+ rail is the output from a simple parallel mixer system - each stage being an input to the mixer.

Clearly then the number of stages and those in phase and those out of phase will affect the "sound" of the amplifier.

Conventional design principles regard the junction between the plate load resistor and the immediately adjacent filter cap as being at AC "earth" - because the filter cap is regarded as being a very low (insignificant) impedance path for the AC in the circuit.

However practical tests reveal a different story.

I submit any given electrolytic cap has different characteristics when comparing its forward and reverse current flow. One way to demonstrate this is to replace an electrolytic in the B+ rail with a non-polarised motor start cap - the difference in tonal quality is huge.

This proves that the junction of plate resistor and filter (signal bypass) cap is not at AC earth at all, but at some point above it - or at best the AC signal circuit will be affected or influenced by the series connected bypass capacitor's inherent internal characteristics.

Now since we are talking a VOLTAGE amplifier we do not need to consider the CURRENT in the B+ rail but the VOLTAGE.

Specifically, the TRANSIENT PEAK VOLTAGE

When a transient signal appears on the B+ rail at any point it will appear across the entire rail - not just at the stage in which it originates.

So if, for example, the phase-splitter B+ voltage momentarily sags, the signal from the previous stage - which does not suffer as much sag because it is a low current stage - will flow to the phase-splitter stage and be mixed with it at the filter cap.

Ohm's Law applies, so wherever there is a voltage difference you will see current flow - in whatever direction it chooses.

The purpose of the series diode in the B+ rail is to prevent SIGNAL voltage from transferring forwards (positive feedback) in the circuit whenever a voltage difference in the B+ rail appears.

It will not of course reduce negative feedback between stages through the B+ rail.

Provided a suitable diode is installed to each and every stage in this way, this simple device prevents the AC in any single-stage circuit from being shared by an adjoining upstream (line-side) stage - thus ensuring all of the signal current is passed through the stage discrete bypass (usually "electrolytic") filter capacitor.

Thus each stage can be optimised in its own right.

8. OPTIMISED ELECTRON STREAM © TECHNOLOGY:
   SYMMETRICAL BALANCED AC SIGNAL DRIVE SYSTEM.

This element of OPTIMISED ELECTRON STREAM © TECHNOLOGY describes the design principle wherein the AC signal drive system circuit comprises a symmetrical balanced AC signal drive system whereby the AC signal OUTPUT from the Driving stage circuit and the AC signal INPUT of the Driven stage circuit must both be directly connected to a common central axis at reference voltage potential.

That is to say, in a push-pull amplifier stage, the mid-point central axis of the AC push-pull signal input voltage MUST be directly connected to the mid-point central axis of the AC push-pull signal output voltage - ie the INPUT voltage to the driven stage.

Transformer Coupling/Driver System

In a conventional transformer coupled circuit, the supply terminal of the single-ended driving side, or centre-tap of the push-pull driving side is earthed via the B+ bypass cap.

In this case, the return circuit for the AC signal is through the transformer primary back to the driver cathode via that B+ bypass cap.

Being connected to earth it follows that the driver cathode bias resistor should be also connected to earth. In the diagram below that would be via a centre-tap on the driver Triode AC filament transformer.

In some Class B designs using zero bias tubes, and in a cathode bias design, the centre-tap is usually connected to ground as shown.
But in a fixed bias design, the centre-tap of the transformer secondary is usually connected to the bias supply.

Thus when the centre tap of the secondary is connected to the bias supply then the primary and secondary centre-taps do not share a common connection - except through the bias supply earth point, which is at positive polarity in respect to the bias voltage.

This can be seen in the following design, where the single-ended driver is coupled to a push-pull output stage.

Note the cathode bias resistor and bypass capacitor in the driver stage are grounded but the centre-tap of the transformer secondary is connected to the negative voltage DC bias supply.

But being a transformer none of that matters, because the primary and secondary are two completely independent and isolated circuits.

**RC Coupled Driver Stage**

However when a tube RC coupled driver circuit is used with either plate or cathode output - then the two circuits must share a common in and out AC signal axis - or else the sound will be affected.
In a cathode biased amplifier the requirement for driving and driven circuits to share a common connection is normal, conventional design practice. A typical standard configuration is shown in Fig 1.

Notice how the central axis of the driving and driven circuits is common. In this case the central axis is at ground potential.

Since the circuitry in both halves of the push-pull circuit are symmetrical and exactly equal it follows that the AC signal voltages in both halves of the push-pull circuit are symmetrical and exactly equal.

However this is not the case with fixed bias amplifiers.

**Fig 2 and 3: Fixed Biased Output Stage**

**Fig 2** shows a conventional fixed bias circuit.
Fig 3 shows a conventional fixed bias circuit with the bias supply shown.

Notice how these circuits also appear to be balanced each side of the push-pull central axis.

However these designs are not balanced and are not symmetrical.

Further explanation is provided below.

Fig 4: OPTIMISED ELECTRON STREAM © TECHNOLOGY Fixed Bias Symmetrical Balanced Drive System.
Notice how this circuit appears to be the same as Fig's 2 and 3.

However there is a subtle difference.

Notice how the Cathode circuit of the driving stage is not connected to ground - as is conventional design practice - but to the bias supply for the driven stage.

This is the profound difference.

Further explanation is provided below.

**Fig 6: Conventional Fixed Bias System.**

Fig 6 shows the AC signal path in a conventional fixed bias system.
Notice how the AC signal must pass through the bias supply components - particularly the bypass electrolytic filter capacitor (usually of the electrolytic variety). In this case, the bias supply shown is simple, but in most designs the bias supply is complex and often comprises chokes and other harmonic producing or refining components - in complex inter-relationships.

Moreover, it is common practice to use half-wave rectification in bias supplies, so the residual ripple voltage will appear as a series of pulses in series with the grid driving circuit.

Consideration must also be given to the effects of spurious harmonic and transient spike signals injected into the bias circuit from the bias supply mains transformer.

Since this part of the driving circuit is common to both halves of the push-pull drive, it follows that the signal will ALWAYS be modified by the bias supply characteristics.

If that was not enough to contend with, it can also be seen that the bias supply negative DC voltage is permanently in the signal circuit.

Furthermore, the bias voltage is offset negatively to the centre-line axis of the signal voltage, which is nominally at ground potential. The greater the applied bias voltage the greater the offset.

Since the AC signal alternations in both halves of the push-pull circuit have both positive and negative polarity, it follows that the bias supply voltage will enhance the signal in the negative alternation and offset the signal in the positive alternation.

This DC voltage and current source will try to support the flow of AC signal sourced energy to the grids when grid current flows in Classes AB1 and AB2 or B - and also Class A if gas is present in the power tubes. However to get to the grids it must first pass through the driving tube circuit. Since the interstage coupling capacitor will not pass DC it follows that the DC component of grid drive power will be dissipated into the plate resistor of the driving tube.

But along the way it can increase the cathode bias voltage of the driving tube (which will attenuate the signal) whilst simultaneously reducing the plate voltage (which will attenuate the signal and reduce AC output voltage) - thereby affecting the capability of the driving stage to respond to the signal input.

Since the plate load resistor of the driving tube provides an alternative return circuit (to ground) for the signal voltage it follows that the conventional fixed bias configuration which adds DC currents into the signal circuit includes elements guaranteeing circuit instability. When negative loop feedback is added to such a circuit - eg from the speaker secondary windings of the output transformer back to the driving stage - then the result must be difficult to predict or control.

Finally, the bias supply final shunt load resistor is in series with the output tube grid resistor and forms an integral part of the grid to cathode circuit of the output tubes. It is common to see relatively high values of bias supply final shunt load resistor compared with the output tube grid resistor value - eg 47k to 100k. Sometimes complex bias adjusting networks are also in there. It follows that the closer the (total) bias supply resistor is to the grid resistor value then the more effect the bias supply characteristics will have upon the AC signal behaviour.
Fig 5 shows the symmetrical balanced AC signal drive system whereby the AC signal OUTPUT from the Driving stage circuit and the AC signal INPUT of the Driven stage circuit have a common central axis at reference voltage potential.

In this example, the bias is set at -40 VDC.

Notice how using this system as shown in Fig 4, the signal path circuits on both sides of the push-pull circuit are exactly equal and balanced - in a similar manner to that of Fig 1: Cathode Bias Output Stage.

Moreover, the signal path is direct between both driving and driven stages and is completely independent of and therefore unaffected by the bias supply.

Consequently neither actual bias voltage nor bias supply characteristics will affect the signal circuit.

Note that the grid to cathode circuits of the power tubes is the same for both Fig 5 and Fig 6 designs.

This system is very stable and provides enhanced frequency response and reduced distortion.

It is entirely suitable for a cathode-follower driver stage - ensure the base of the cathode follower load resistor is connected to the bias supply as shown in Fig 5.

An added benefit for a cathode-follower driver system is that the cathode load resistor now spans the bias voltage as well as the B+ voltage. Consequently the cathode follower load resistor may be made substantially larger whilst still maintaining the same plate to cathode voltage in the tube. This can offer increased output voltage to the driven stage.

Load Resistor

Generally speaking, the greater the load resistance/impedance to the driving stage the higher the output capability.

However there are practical limits to this objective since output tube grid circuit resistance must be held within manufacturers’ published specifications.

To maximise the driver stage load whilst minimising driven stage grid circuit resistance the RATIO of driver stage load plate resistor to driven stage grid circuit load resistor should be held within the range of about 1:1 to 1:2.

Most of us have a junk box stock of perfectly good tetrodes, pentodes or beam power tubes just waiting to be used - so why not experiment and prove the benefits of OPTIMISED ELECTRON STREAM © TECHNOLOGY to yourself.
There is no restriction or cost imposition upon the home hobbyist constructor to using these concepts - the only restriction is on commercial exploitation - so if you do not like it do not do it.

If you want your hi-fi to improve its performance at minimal cost to you then experiment. The concepts presented here do work and cost very little to implement.

However to those who say that a product is only as good as what you pay for it, then these concepts are of no value to you because they are free. You would be wiser to spend a hundred grand on a commercial system and feel better. While you are so doing, ask the manufacturer to justify the circuit design and component choices to you - ie why the design is what it is and not some other alternative approach. That is “why is it better?”

To those who consider relating these concepts to RF applications - this is an audio focused site - experiment at your own risk. It may be safer to stay with the tried and true - waste a little power and live with it.

However RCA, in their Transmitting Tube Manual TT4, say at Page 44 - "The only restrictions on tube operating values are those imposed by the published maximum ratings." The OPTIMISED ELECTRON STREAM © TECHNOLOGY design concepts presented above should enable designers to withdraw operating conditions back into specification whilst improving performance.

Finally, an OES tube amplifier can only and will always sound like a tube amplifier. The OES concept is limited to and by the vacuum tubes it relates to.

HAPPY CONSTRUCTING!!

MAY YOUR PROJECT BE A SUCCESS!!

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REMEMBER:

- ALWAYS TAKE CARE WHEN WORKING WITH HIGH-VOLTAGE -

DEATH IS PERMANENT!!