

Baking valves

by Morgan Jones

Although valves are popular with audiophiles and musicians, it is perhaps less well known that valves are extremely popular in recording studios, and that all the major microphone manufacturers feature at least one microphone with a valve head amplifier in their condenser microphone range. Valve microphones tend towards large capsule designs - around 18mm in diameter - and they are popular for vocals. Because a microphone level signal is, by definition, uncontrolled, it is common for recording engineers to want the entire vocal channel to have valve electronics until it reaches the channel fader. Consequently, other valve studio electronics includes outboard microphone channels, equalisers, and compressor/limiters.

Although there is a demand for audio valves, in comparison with the electronics market as a whole, the audio valve market is minuscule and not worthy of significant investment. Unfortunately, manufacturing valves is a high-technology enterprise, so production runs must be maximised, resulting in very few small-signal types currently being made. Worldwide, there is only a handful of factories producing audio valves, yet despite the paucity of manufacturers, production runs are short, so quality control is difficult and contemporary production engineers must rediscover the skills of their Cold War counterparts in the 1950s and 1960s.

The Cold War generated huge stockpiles of unused valves that are gradually being released by governments. These valves are charmingly termed 'new old stock' - or NOS for short. Because these valves were made by manufacturers at the height of valve production, quality control is less likely to be an issue, so many users prefer NOS to current production valves. However, there can be problems with NOS valves, and scarcity causes audio valves such as the GEC KT66 or KT88 to be extremely expensive, so a potential buyer will want to be sure that the product still meets its original specification - which is no mean feat after more than forty years of possibly haphazard storage.

To understand one of the most common problems of NOS valves, it is worthwhile to briefly review the physics of the thermionic valve...

Thermionic emission and diodes

All metals have free electrons within their crystal structure, so some electrons must be at the surface of the metal. However, the atoms and electrons constantly vibrate due to thermal energy, so if the metal is heated sufficiently, some surface electrons may gain sufficient kinetic energy to completely escape the metal. The heated metal in a valve is the cathode. When it is heated to a temperature determined by the work function of the metal, an electron cloud, or space charge, forms at its surface. Because electrons are negatively charged, and like charges repel, the cloud eventually attains a sufficient charge to prevent other electrons escaping from the surface, and an equilibrium is reached.

If a conductive plate, or anode, is placed some distance from the cathode, and charged to a positive voltage, electrons will be attracted from the cloud towards the anode. The electron cloud has now been depleted, and no longer repels electrons so strongly, so more electrons leave the surface of the cathode to replenish the electron cloud.

Current cannot flow in the opposite direction because only the cathode can emit electrons, and only the positive anode can attract electrons.

Electron velocity

At the instant that an electron leaves the cloud, it has almost zero velocity, but it is constantly accelerated by the electric field between the cathode and anode, and acquires energy proportional to the accelerating voltage:

$$E = q_e V = \frac{1}{2} m_e v^2$$

Rearranging, and solving for velocity:

$$v = \sqrt{\frac{2Vq_e}{m_e}}$$

The ratio q_e/m_e is the electron charge/mass ratio and has an approximate value of $1.7588 \times 10^{11} \text{ C/kg}$. If 100V is applied between the anode and cathode, the electrons will collide with the anode at a velocity of around $6 \times 10^6 \text{ m/s}$, (22 million km/h, or 13 million mph). Note that the cathode to anode distance is immaterial because an infinite distance would allow an infinite time for acceleration, so the collision velocity would still be reached even if the rate of acceleration was very low. When the speeding electrons are abruptly halted by the anode, their kinetic energy is converted into thermal energy and it is this heat that is responsible for the anode dissipation rating.

Many effects within valves can be understood by having an appreciation of the collision velocity of the electrons as they hit the anode.

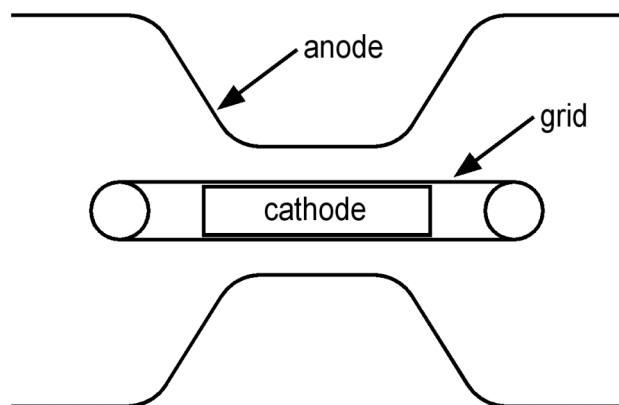
Ionization current

The vacuum in a valve cannot be perfect so there will always be stray gas molecules between the cathode and anode. As an electron nears the anode it has considerable energy, and if it collides with a stray gas molecule it can easily dislodge an electron from that molecule, which will promptly be captured by the anode. The gas molecule that has been stripped of an electron is known as a positive ion, and because it is positively charged it is repelled from the anode and accelerates towards the grid/cathode structure in exactly the same way that the negatively charged electrons were accelerated towards the anode.

Because the gas ion contains at least one neutron, it is thousands of times heavier than an electron and does not attain the final velocity of the speedy electrons. Nevertheless, if an ion does manage to reach the cathode, it is likely to collide with considerable momentum and damage the fragile emissive surface. This process is known as cathode stripping, and if it occurs for long enough it can destroy the emissive properties of the cathode, ruining the valve.

The control grid

In order to control the flow of electrons from cathode to anode, and produce amplification, a grid of fine wires is placed between the cathode and anode:



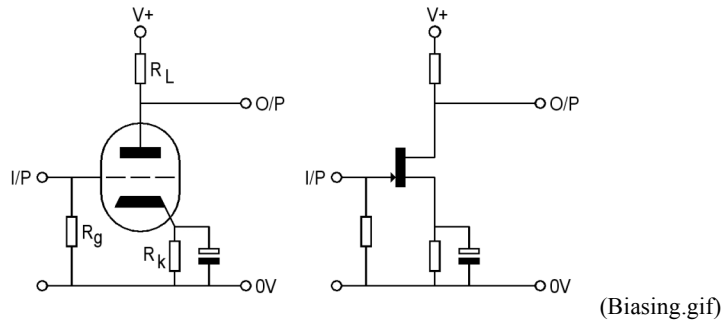
(417A.gif)

For clarity, this cross-sectional plan view shows a clear gap between grid and cathode but most practical valves have minuscule spacing.

To maximise its effect, the control grid is placed close to the cathode surface, where the velocity of the electrons is low, rather than near the anode, by which time the electrons have acquired considerable momentum, and are not easily repelled.

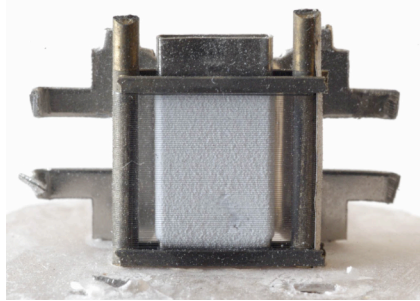
The control grid and ionization current

Just like JFETS, valves are voltage-controlled devices and their grid must be biased negatively with respect to the cathode in order to control anode current.²



Caption: The value of the cathode resistor R_k sets the anode current in this self-biased stage.

Typically, a $1\text{M}\Omega$ grid-leak resistor (R_g) holds the grid at 0V . The value of the cathode bias resistor in conjunction with individual valve characteristics determines the anode current because it sets the grid to cathode voltage, V_{gk} . From the point of view of a gas ion, the grid and cathode are at very nearly the same potential, so they are equally attractive. As a result, the probability of a gas ion striking the grid is largely determined by the relative dimensions of the grid wire diameter and its pitch. See Fig. 3.



(417A.jpg)

The fine grid wires in the frame-grid 417A are so close to the cathode that the emissive surface can be seen to be quite coarsely textured. Note that the emissive surface was damaged during manufacture.

The grid wire diameter is quite fine compared to the gaps between the wires, so most of the gas ions strike the cathode. Whether the ions strike the grid or the cathode, they are immediately discharged by a balancing number of electrons flowing up through the external paths to ground.

Even though only a little of the ionization current may flow into the grid circuit, it is usually the grid ionization current that is significant, not the cathode ionization current. This is because the external grid circuit typically has a much larger resistance to ground than the cathode circuit and therefore develops a larger voltage.

Bias stability

If the grid ionization current is sufficiently large, it can develop sufficient positive voltage across the grid-leak resistor that V_{gk} is reduced, causing anode current to increase significantly. Because power valves are usually operated at maximum anode dissipation, valve manufacturers specify a maximum value of grid-leak resistor to ensure that any change in V_{gk} due to grid ionization current is kept within safe limits. Because cathode bias is self stabilizing, the permitted value of grid-leak resistor for this form of bias is much larger than that permitted for grid or fixed bias.

Noise

Since the formation of ions and their subsequent discharge by the grid is random, the ionization current must have a noise component. This noise current is converted by the grid-leak resistor into a noise voltage, and is amplified by the valve.

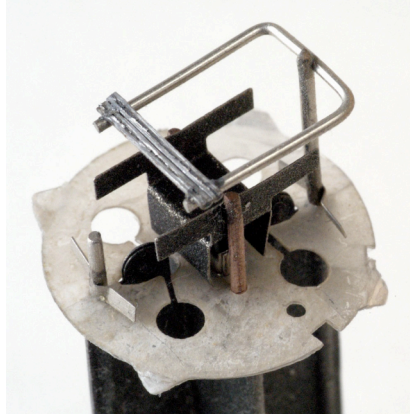
It is usual for high resistance circuits such as condenser microphone head amplifiers to use $500\text{M}\Omega$ grid-leak resistors, so ionization current must be minimised to avoid degrading the signal-to-noise ratio.

Minimising ionization current

Clearly, the fewer gas molecules within the valve envelope, the lower the ionization current, so valve manufacturers strive to achieve as hard a vacuum as possible. During manufacture, most of the gas in the valve is pumped out, but some gas remains that cannot be removed by pumps. This is removed by the getter. The getter is a metal structure, often near the top of the valve, coated with a highly volatile powder - usually a barium compound similar

to the cathode emissive surface. Once the valve has been pumped and sealed, the getter is ignited in order to react with the remaining gas, thus consuming it. The force of the consequent explosion throws molten barium onto the inside of the envelope to give the familiar mirrored coating.

The explosion is initiated electrically. Metal envelope valves require the ignition current to be directly passed through the getter's metallic supporting structure, whereas the more common glass envelope valves have their ignition current induced via an external RF field by shaping the getter as a short-circuited loop aerial:



(A2293.jpg)

This GEC A2293 has a square loop aerial with one side of the square formed of a triangular trough filled with the getter material to be ignited.

Some of the getter material is inevitably consumed by the explosion, but the remainder continues to absorb gas molecules throughout the life of the valve because gas seepage inevitably weakens the valve vacuum. Gas can seep in either via the seals where the leads leave the envelope, or by outgassing from a hot anode. Gas molecules must touch the getter to be consumed by it, but this is assured by normal Brownian motion provided that the heater reaches operating temperature before HT is applied to the anode.

If the entire getter material should be consumed, perhaps because of a microfracture in the glass envelope, the mirrored coating turns white, so this is clear evidence of catastrophic vacuum failure.

Cathode poisoning due to gas

Since the cathode emissive material is of a very similar composition to the getter material, it follows that a cathode at 800C could be more effective at reacting with stray gas molecules than a mildly warm getter. Unfortunately, in doing so, the cathode emissive surface becomes poisoned and loses emission, possibly ruining the valve.

Softness

NOS valves are likely to have been sitting in a cold warehouse for at least twenty, and possibly fifty years, so it should come as no surprise that the vacuum deteriorates. In theory, the getter should consume the molecules to maintain the vacuum, but the most common cause of failure in NOS valves is deterioration of the vacuum - this is often referred to as the valve having gone 'soft'.

Valve testers

Because excessive grid or gas ionization current is a known failure mode, most valve testers incorporate some means of quantifying this crucial parameter. As an example, the AVO VCM163 allows the user to set anode and cathode conditions, then use a 100 μ A meter to measure grid current.

Some power valves might be considered to be perfectly acceptable when passing 10 μ A of grid current. However, 1 μ A would be unacceptable in a small signal valve intended to be operated with $V_{gk} = -2V$ and employing a 1M Ω grid-leak resistor.

Results of valve tests

In April 2000, the author bought a batch of twenty-nine Siemens D3a NOS high slope pentodes; g_m is around 30mA/V, maximum anode dissipation is 4W, and it is typically biased with a V_{gk} of around -2V. Strapped as a triode, $\mu = 80$. The combination of these characteristics makes it a popular choice for a cathode follower or first stage in an RIAA preamplifier.

The batch was tested for emission and gas current at the proposed operating point on an AVO VCM163, and the

raw results are shown in Table 1.

Table 1: Test results of triode-strapped D3a on AVO VCM163 valve tester with $V_a = 175V$ and $V_{gk} = -2V$.

Valve	I_a (mA)	g_m (mA/V)	I_g (μA) before	I_g (μA) after
1	15	28	1	0.13
2	21	35	1	0.20
3	6.5	-	soft	0.15
4	24	40	1.5	0.22
5	23	41	1.5	0.24
6	21	34	1	0.12
7	20	33	1	0.06
8	15	29	1	0.17
9	21.5	34	1	0.14
10	20	35	1	0.05
11	23	40	1	0.21
12	5	-	soft	1.20
13	15	27	1	0.22
14	25	40	1	0.19
15	21	32	1	0.22
16	16	28	1	0.30
17	15	29	1	0.17
18	4	-	soft	1.20
19	20	37	1	0.12
20	19	32.5	1	0.14
21	19.5	35	1.5	0.44
22	19.5	35	1	0.23
23	9	-	soft	1.3
24	22	33	1	0.24
25	22	36	1	0.27
26	22.5	38	1	0.19
27	3	-	soft	0.17
28	20	37	1	0.22
29	25	39	1	0.20

Mean	20.25	34.5	1.06	0.195
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The results were disappointing. Five valves had poor emission, and the remainder passed a microamp or more of gas current. Worse, many valves exhibited unstable anode current. The 382 date code on the envelope suggests that these NOS valves were made in March 1982, so they were eighteen years old at the time. It seemed likely that the valves with very low emission failed due to manufacturing defects. The remaining valves were not quite acceptable, yet it seemed unlikely that they had gross defects, but more probable that the getter had failed to mop up minor leakage over the years.

Although operating the valves for a few hours might clear the residual gas, this would carry a risk of cathode poisoning, cathode stripping, or possibly thermal runaway due to unstable anode current. Rather than risk damaging the new valves, the author decided to experiment with some expendable valves. At the time, the EF184 RF pentode could barely be given away, so the tests were repeated with a mixed batch of twenty-nine NOS EF184 of differing ages and manufacturers. The results are summarised in Table 2.

Table 2: Test results of triode-strapped EF184 on AVO VCM163 valve tester with $V_a = 175V$ and $V_{gk} = -2V$.

Quantity	I_g (μA)	R_{hk} ($M\Omega$)	Comments
16	-	>25	No defects
1	0.5		
6	1		
3	2		
1	-	25	
1	-	12	low emission
1	-		low emission

There are some 'fixes' for low-emission and poor heater-to-cathode resistance that will be covered later in this article, but ten valves with the same symptoms as the faulty D3a could now be sacrificed to science with impunity. Since chemical reactions double their rate for every $10^\circ C$ rise in temperature, perhaps the getter could be provoked into restoring the vacuum by heating the valves in a kitchen oven? Maximum envelope temperature is typically specified as $200^\circ C$, but kitchen ovens are hardly precision devices, so the author's oven was set to 'warm' (which turned out to be roughly $100^\circ C$ or $212^\circ F$). Three hours later, the valves were removed and re-tested. Gratifyingly, there was a noticeable improvement, with all ten valves registering approximately half their previous gas current.

Clearly, the hypothesis was plausible, but the process was rather slow and it was a hot summer, so leaving the oven on for a long time was not attractive. A back-of-an-envelope calculation suggested that reducing the residual gas and gas current to $<1\%$ of its original value would require more than $7 \times 3 = 21$ hours ($27 = 128$). A cookery book suggested that gas Mark 2 is around $130^\circ C$ ($266^\circ F$), and as the oven temperature had previously been measured with a thermocouple probe as being approximately $100^\circ C$ ($212^\circ F$), this should give an eight-fold improvement and reduce the time required to 7 hours.

Although the AVO valve tester was capable of indicating the gas current and its improvement, it could not make an accurate measurement, so it was modified by breaking its grid bias supply and connecting a Fluke 89 IV - ammeter in series to enable a better reading.

The D3a valves were added to the EF184, the oven was set to gas Mark 2 - later measured to be $120^\circ C$ ($248^\circ F$) - and the valves were left overnight for 13 hours. On removal, the valves were tested for gas current, and the results after baking were added to Table 1.

Although the gas current measurement before baking was necessarily somewhat inaccurate - $1\mu A$ on a $100\mu A$ FSD movement - the average improvement in gas current due to baking was a factor of five. Testing the baked valves showed that although anode current and gm were noticeably lower for all valves, they were far more stable. Further, they now agreed closely with a known good valve, suggesting that the previously high and unstable characteristics were a direct consequence of the grid gas current.

Although the baked valves showed an improvement in gas current, the very soft valves remained low emission and were set aside.

Baking tips

Valves that have no manufacturing defects but have been in storage for many years may accumulate a little gas. If there is any suspicion that this may have occurred to any significant degree, it is better to bake the valves before testing rather than risk damaging fragile oxide-coated cathodes.

Grid ionization current can easily be the dominant form of noise in high resistance circuits, such as condenser microphone head amplifiers. As a result, it makes sense to routinely bake valves intended for this type of use before selecting for low noise.

Although valves with glass button bases may be safely baked at 120°C (248°F) for 12 hours without damage, baking valves with phenolic bases at this temperature causes the surface of the base to erupt. This was not a welcome discovery...



More important than the spoiled appearance, the erupted centre spigot makes the valve difficult to plug into a socket.

Sadly, the author doesn't have sufficient sacrificial phenolic-based valves to reliably determine a safe phenolic baking temperature, although he suspects that 100°C (212°F) might be safe.

Because surface contamination on the glass envelope of the valve produces leakage paths that can cause noise, it is usual to clean the envelope scrupulously and subsequently only handle the valve with clean cotton gloves.³ Cleaning should be done before baking, otherwise it might not be possible to remove any hardened contamination...

Unfortunately, as a consequence of baking, the painted lettering on the valve shows a little discolouration, appearing as if the valve has had a few hours use.

Other valve 'fixes'

Although careful baking does not damage valves, these final two 'fixes' carry considerable risk.

Poor R_{hk}

The consequences of poor heater-to-cathode insulation depend greatly on the application and on V_{hk} .

A typical amplifier with an EL34 output valve passing a cathode current of 70mA will have its cathode at +35V. If the heater is grounded, $R_{hk} = 100k\Omega$ will cause a negligible 350µA (0.5%) to leak from the cathode, and any noise created by that leakage current will be short-circuited by the cathode bypass capacitor.

Conversely, a cathode follower used in an active crossover feeding a power amplifier requires a signal-to-noise ratio of at least 90dB even though the signal may only reach a maximum of $2V_{RMS}$. Although the resistance looking into the cathode is low, it is not a short circuit. Worse, V_k may well be elevated to >100V, so a high value of R_{hk} is essential to ensure that leakage currents do not degrade the S/N ratio.

Contamination causing poor R_{hk} can sometimes be burnt away on a valve tester. The tester should be set to test R_{hk} with the normal heater voltage applied and the cathode allowed to warm to its normal temperature. R_{hk} should be closely monitored and heater voltage increased to 150%. The resistance shown on the tester will fall, but with luck, the rate of fall will slow - or even reverse. Assuming this effect occurs, immediately reduce the heater supply, and allow the valve to cool. The result may be an improved R_{hk} . Some valves cannot be recovered by this technique, and others may need repetition to make them acceptable, but the overall success rate is quite good.

The risk is that by deliberately overheating the cathode, some of the emissive surface may be evaporated and deposited onto the nearby grid. The grid now has its own emissive surface, and if the valve is operated close to maximum anode dissipation, it may become warm enough to emit electrons, causing thermal runaway, leading to the valve's ultimate destruction.

Low emission due to cathode poisoning

Valves that have been operated for a long time at very low anode currents can develop a cathode interface resistance that effectively limits electron emission but the 'fix' is violent.

The valve is heated with 150% heater volts, anode voltage is set to a slightly higher than normal design value, and V_{gk} is adjusted until sufficient electrons are dragged from the cathode to make the anode glow deep cherry red. The valve is left to fry for perhaps five seconds before all voltages are removed. With a bit of luck, the control grid has not been covered in evaporated cathode material. When tested a few minutes later, the valve might show better emission.

Rejuvenation carries a very high risk, and the results are not generally very good, so the process is only really worthwhile on picture valves. Dedicated television tube rejuvenators have been made, but the risk of destroying the tube is high, nevertheless, tube replacement is expensive, so rejuvenation may be considered to carry an acceptable risk.

References

1. 'Principles of electron tubes', pp. 112, 123, J W Gewartowski & H A Watson. (1965) Van Nostrand. Princeton. New Jersey.
2. 'Valve Amplifiers' 3rd Ed. Morgan Jones. (2003) Newnes 0-7506-5694-8
3. 'Electrostatic cardioid microphone M7', BBC Technical Instructions (Recording), Instruction S.2 Section 5.3.

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