Amplification Factor or Plate Resistance? …by Earles L. McCaul

• Is r_p more important than mu?

To many people, the most important characteristic of a vacuum tube is its amplification factor **μ**. When swapping tubes in a guitar amplifier, however, this is simply not the case. Of a vacuum tube's three operating characteristics: dynamic plate resistance $\mathbf{r_p}$, transconductance $\mathbf{g_m}$, and amplification factor **μ**, two are explicit values and one is an implicit value. The $\mathbf{g_m}$ and $\mathbf{r_p}$ values are explicit because they come directly from the tube's operating voltages and currents. **μ**, on the other hand, is an implicit value that is mathematically derived from the product of plate resistance and transconductance:

$$\mu = g_m \times rp$$

$\mathbf{g_m}$ and $\mathbf{r_p}$ are almost (but not exactly) inversely related. That is, as $\mathbf{g_m}$ increases with increasing plate current, $\mathbf{r_p}$ proportionately decreases. This inverse relationship causes **μ** to be virtually a constant that varies typically by less than 10 to 15 percent among vacuum tubes of the same type.

The vacuum tube operating characteristics $\mathbf{g_m}$, $\mathbf{r_p}$, and **μ** are open-circuit values determined with no external loads applied. In the real world, however, tubes operate in circuits having both input and output loads. It is the effect of these loads (especially upon the plate) that make $\mathbf{r_p}$ more important than **μ**. Here's the reason why.

When resistances are connected in parallel (symbol ||), their resulting resistance is always less than the smallest resistance value. For example, consider two resistances, $\mathbf{R_A = 10k\Omega}$ and $\mathbf{R_B = 100k\Omega}$, connected in parallel. The effective parallel resistance is

$$R = (R_A||R_B) = (R_AR_B)/(R_A+R_B) = (10k)(100k)/(10k + 100k) = 9.1k\Omega$$

The same thing happens when a tube is operated with a plate load resistor $\mathbf{R_P}$. This external resistance loads $\mathbf{r_p}$ just like the resistance $\mathbf{R_B}$ loaded resistance $\mathbf{R_A}$ in the example above. For instance, operating a 12AX7 ($\mathbf{r_p = 62.5k\Omega}$) with a plate load resistor of $\mathbf{R_P = 100k\Omega}$ produces a circuit gain of only 61.5, significantly less than its amplification factor of 100. This is because the *effective* plate resistance $\mathbf{r_p'}$ is no longer 62.5KΩ ohms—it's only 38.5kΩ:

$$r_p' = r_p|| R_P = (62.5k)(100k)/(62.5k + 100k) = 38.5k\Omega$$

where, for a typical 12AX7 preamp,

$\mathbf{r_p = 62.5k\Omega}$
$\mathbf{R_P = 100k\Omega}$

When the transconductance $\mathbf{g_m}$ is multiplied by the *effective* plate resistance $\mathbf{r_p'}$, a much lower *effective* amplification factor **μ'** value is obtained:

$\mu' = g_m \times \underline{r}_p'$

For the 12AX7, where g_m **= 0.0016A/V**, we get an *effective* amplification factor of

$\mu' = (0.0016)(38.5k) = 61.5$

When we consider the output loading of the next circuit, such as a second preamp or a tone stack, then the effective plate resistance is even lower. For example, assume the 12AX7 plate load resistor $R_P = 100k\Omega$ feeds its signal into the next circuit having a resistance of $R_o = 500k\Omega$. Then $\underline{r}_p$ equals three loads in parallel and we get

$r_p' = r_p || R_P || R_o = 1/(1/r_p + 1/R_P + 1/R_o) = 35.7k\Omega$
$\mu' = (0.0016)(35.7k) = 57.1$

Thus, while the open-circuit gain of a 12AX7 is 100 with no load, its gain in a real world circuit is in the range of 57 to 62, depending upon R_P and R_o.

In conclusion, **μ** represents the theoretical upper limit of the tube with no load, whereas **μ'** represents what you actually get in a realistic circuit.

Just as circuit amplification is dependent upon r_p', so too is the circuit's treble response. If we define the circuit's bandwidth **BW** as the -3dB cutoff frequency, representing a frequency above which the amplifier's response is significantly attenuated, then

$BW = 1/(2\pi \underline{r}_p C)$

where $r_p' = r_p || R_P || R_o$ and **C** is coupling capacitor that connects the signal to the next circuit.

When we swap tubes, it's the r_p value of the new tube interacting with R_P, R_o, and **C** of the existing circuit that causes the sometimes subtle changes in amplification and tone (frequency response) that we hear.

To understand why plate resistance is more significant than amplification factor, take a look at Table 1 listing seven popular preamp tubes and depicting their operation with circuit load resistances of $R_P = 100k\Omega$ and $R_o = 500k\Omega$ and a ***fictitious*** coupling capacitor of $C = 446\mu F$, i.e.:

$r_p' = (rp||RP||Ro)$
$\mu' = (gm \times r_p')$
$BW = 1/(2 \cdot \pi \cdot r_p' \cdot C)$

Notice how high-mu tubes with high plate resistance values suffer much greater in-circuit loss of gain than do tubes with low plate resistance values. Specifically, the high-mu 12AX7 (100) with r_p = 62.5kΩ suffers the greatest in-circuit loss while the medium-gain 12AV7 (41) with r_p = 4.8kΩ and the low-gain 12AU7 (17) with r_p = 7.7kΩ suffer the least in-circuit losses.

Table 1 - Preamp tubes sorted by amplification factor.

TUBE	μ	gm(A/V)	$r_p(\Omega)$	Pp(W)	$r_p'(\Omega)$	μ'	BW(hz)
12BZ7	102	0.0032	31,800	1.50	23,017	73.7	15,517
12AX7	100	0.0016	62,500	1.20	35,714	57.1	10,000
5751	70	0.0012	58,000	1.10	34,198	41.0	10,443
12AT7	60	0.0055	10,900	2.50	9,639	53.0	37,051
12AV7	41	0.0085	4,800	2.70	4,539	38.6	78,690
12AY7	40	0.0018	22,800	1.50	17,902	31.3	19,950
12AU7	17	0.0022	7,700	2.75	7,049	15.5	50,668

Now look at Table 2, it clearly shows that a higher value of $\mathbf{r_p}$ reduces the treble response represented by **BW**. This means that tubes with low $\mathbf{r_p}$ values have less treble attenuation. Note also that the variation of effective amplification factor is not nearly as great. Table 2 shows the same results arranged according to bandwidth.

Table 2 - Preamp tubes sorted by bandwidth.

TUBE	μ	gm(A/V)	$r_p(\Omega)$	Pp(W)	$r_p'(\Omega)$	μ'	BW(hz)
12AV7	41	0.0085	4,800	2.70	4,539	38.6	78,690
12AU7	17	0.0022	7,700	2.75	7,049	15.5	50,668
12AT7	60	0.0055	10,900	2.50	9,639	53.0	37,051
12AY7	40	0.0018	22,800	1.50	17,902	31.3	19,950
12BZ7	102	0.0032	31,800	1.50	23,017	73.7	15,517
5751	70	0.0012	58,000	1.10	34,198	41.0	10,443
12AX7	100	0.0016	62,500	1.20	35,714	57.1	10,000

We see that substituting a 5751 for a 12AX7 (or ECC83, 7025, etc.) typically reduces circuit gain by 28 percent and slightly increases bandwidth by 4 percent. Similarly, substituting a 12AY7 for a 12AX7 reduces circuit gain by almost half (45 percent) but nearly doubles the bandwidth.

Greater bandwidth has the potential to translate into more sparkle and chime in the output. It is important to note, however, that changing a preamp's bandwidth has no affect on the response of subsequent circuits in the signal path. An increased treble response in one stage won't make any difference in tone if subsequent stages have significantly less bandwidth. This is an important reason why swapping preamp tubes seems to produce vague and subtle tonal changes, while swapping output power tubes, located in the last stage of the signal path, often produces dramatic sonic differences.

• Summary: Mu (μ) is what the tube *alone* is capable of—mu' (μ') is what you *actually* get in the circuit. R_p ***is*** more important than mu when in-circuit gain (AV) and high-frequency response are the tube's most important performance criteria.