

Why do Tubes sound different?

From Old Tele Man;

TUBES: it's RP, not MU, that's important!

It's the RP-value, NOT the MU-value that's Important!

To many people, the most important characteristic of a vacuum tube is its Amplification Factor (μ). Unfortunately, this is not true.

Of the vacuum tubes' three operating characteristics – Dynamic Plate Resistance (r_p), Transconductance (g_m) and Amplification Factor (μ) – two are explicit values and one is an implicit value. The g_m and r_p values are explicit because they come directly from the tubes' actual operating voltages and currents. The μ value, however, is an implicit value that is mathematically-derived from the product of the r_p and g_m values:

$$\mu = g_m * r_p$$

G_m and r_p are almost (but not exactly) inversely related. That is, as g_m increases with increasing plate current, r_p proportionately decreases. This inverse relationship causes μ to be virtually a constant that typically varies less than 10–15%.

The vacuum tube operating characteristics g_m , r_p and μ are “open-circuit” values, that is, they are calculated with NO external loads applied. In the real world, however, tubes are operated in circuits having both input and output loads. It is the effects of these “loads” (especially upon the plate) that make r_p more important than μ . Here's why...

When resistances are connected in parallel (symbol “||”), their resulting resistance is always LESS than the smallest resistance value. For example, consider two resistances, $A = 10K$ ohm and $B = 100K$ ohm, connected in parallel:

$$R = (A||B) = (A*B)/(A+B)$$

$$R = (10K*100K)/(10K + 100K) = 9.09K \sim 9.1K \text{ ohms}$$

The same thing happens when a tube is operated with a plate load resistor (RP), its r_p value is “loaded” in the same fashion as

resistance-B “loaded” resistance-A in the example above. For instance, operating a 12AX7 ($r_p = 62.5\text{K ohm}$) with a 100K ohm plate load resistor produces a circuit gain of only 61.5, not 100!

Why? Because, the ‘effective’ plate resistance (r_p') is no longer 62.5K ohms – it’s 38% LESS – only 38.5K ohms:

$$r_p' = r_p || R_P$$

$$r_p' = (62.5\text{K} * 100\text{K}) / (62.5\text{K} + 100\text{K}) = 38.46\text{K} \sim 38.5\text{K ohms}$$

...where:

r_p = Tube dynamic plate resistance, ohms (12AX7: 62.5K ohm)

R_P = Circuit plate load resistance, ohms (typically 100K ohm)

Now, when tube g_m is multiplied times r_p' a much LOWER amplification factor (μ') value is obtained because of the LOWER ‘effective’ r_p' value:

$$\mu' = g_m * r_p'$$

...for 12AX7 $g_m = 0.0016 \text{ A/V}$, then:

$$\mu' = (0.0016 * 38.5\text{K}) = 61.5$$

And, when the output loading of the NEXT circuit (tube, tone stack, etc.) is included, the effective plate load becomes even LOWER. For example, assume the 12AX7 plate load resistor $R_P = 100\text{K ohm}$ feeds its signal into a tone stack having a resistance value of $R_o = 500\text{K ohms}$. Now, r_p' becomes three loads in parallel:

$$r_p' = (r_p || R_P || R_o)$$

$$r_p' = 1 / (1/r_p + 1/R_P + 1/R_o)$$

$$r_p' = 1 / (1/62.5\text{K} + 1/100\text{K} + 1/500\text{K}) = 35714.3 \sim 35.7\text{K}$$

$$\mu' = (0.0016 * 35.7\text{K}) = 57.1$$

Thus, while the “open-circuit” gain of a 12AX7 is 100 with no load, its gain in a “real world” circuit (tube with loads) will be nearer to 60 (ie: 57–62), depending upon R_P and R_o .

SUMMARY: “Mu is what the tube (alone) is capable of...Mu’ is what you actually get (in a circuit).”

Additionally, just as circuit AMPLIFICATION is dependent upon r_p , so also is circuit FREQUENCY response or BANDWIDTH (BW), ie:

$$BW = 1/(2*PI*R*C)$$

...where: $R = r_p || R_P || R_o$

So, whenever we “swap” tubes, it’s the r_p value of the new tube interacting with the R_P , R_o , R and C values of the existing circuit that causes the sometimes “subtle” changes in amplification (gain) and tone (frequency response) that we hear.

And, here’s why...

The r_p' values shown in Table 1 represent preamp tube operation with circuit load resistances of $R_P = 100K$ ohms and $R_o = 500K$ ohms, ie:

$$r_p' = (r_p || R_P || R_o)$$

The illustrative bandwidth (BW) values shown in Table 1 were calculated using $R = r_p'$ and an assumed constant fictitious capacitance value of $C = 446\mu F$, ie:

$$BW = 1/(2*PI*R*C)$$

where: $R = r_p'$ and $C = 446\mu F$

Table 1 – Preamp tubes sorted by MU values.

TUBE	mu	gm (A/V)	$r_p(\Omega)$	$P_p(W)$	$r_p'(\Omega)$	mu'	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

As you can see, the greater the r_p' value, the lower the bandwidth! Which means that tubes with LOW r_p values (and thus circuits with LOW r_p' values) will have greater BW and frequency response and proportionately less loss-of-gain (ie: μ') than tubes with HIGH r_p values. Table 2 re-orders the preamp tubes listing by their BW, in descending order.

Table 2 – Preamp tubes sorted by BW values.

TUBE	μ	g_m (A/V)	r_p (Ω)	P_p (W)	r_p' (Ω)	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

Thus, substituting a 5751 for a 12AX7 (or ECC83, 7025, etc.) typically reduces circuit gain by 28% and slightly increases BW by 4%. Similarly, substituting a 12AY7 for a 12AX7 reduces circuit gain by almost half (45%) but nearly doubles the BW. And, remember, the greater the BW, the more “sparkle” and “chime” we’re likely to perceive.

Why only “....likely to perceive”? Because, changing one preamp tubes’ BW does not affect the BW of ANY of the subsequent tubes along the signal path. There might be more frequencies in the drive signal to the following tubes but they will not (usually) be able to pass along those added frequencies to the speaker(s) because their BWs have not changed.

That is ‘why’ swapping preamp tubes seemingly produces vague and subtle, instead of dramatic, tonal changes, while swapping output power tubes (the last tubes in the path) often produces VERY noticeable sonic changes.

Cathode Stripping, The electrons are basically being “yanked” directly from the cathode before there's time or energy enough to coalesce in a “cloud” anymore

...an "old" USN electronics proverb goes:

SHORT = infinite BW, because there's no R working with C to cause an RC rolloff.

OPEN = zero BW, because there's infinite R working with C to cause immediate RC rolloff.

...however, in the 'whole' amp, there's always the inductance (L) of the audio output transformer (OT) to consider to, which typically is *the* limiting factor for both LOW(f_1)- and HIGH(f_2)-cutoff frequencies!

...my illustrative example only includes the tube and the loading its load.