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 (mu). Unfortunately, this is not true.

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

mu = gm * rp

Gm and rp are almost (but not exactly) inversely related. That is, as gm increases with increasing plate current, rp proportionately decreases. This inverse relationship causes mu to be virtually a constant that typically varies less than 10-15%.

The vacuum tube operating characteristics gm, rp and mu 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 rp more important than mu. 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 ~ 9.1K ohms

The same thing happens when a tube is operated with a plate load resistor (RP), its rp value is “loaded” in the same fashion as resistance-B “loaded” resistance-A in the example above. For instance, operating a 12AX7 (rp = 62.5K ohm) with a 100K ohm plate load resistor produces a circuit gain of only 61.5, not 100!

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

rp’ = rp||RP

rp’ = (62.5K*100K)/(62.5K + 100K) = 38.46K ~ 38.5K ohms

...where:
rp = Tube dynamic plate resistance, ohms (12AX7: 62.5K ohm)
RP = Circuit plate load resistance, ohms (typically 100K ohm)

Now, when tube gm is multiplied times rp’ a much LOWER amplification factor (mu’) value is obtained because of the LOWER ‘effective’ rp’ value:

mu’ = gm * rp’

...for 12AX7 gm = 0.0016 A/V, then:

mu’ = (0.0016 * 38.5K) = 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 RP = 100K ohm feeds its signal into a tone stack having a resistance value of Ro = 500K ohms. Now, rp’ becomes three loads in parallel:

rp’ = (rp||RP||Ro)

rp’ = 1/(1/rp + 1/RP + 1/Ro)

rp’ = 1/(1/62.5K + 1/100K + 1/500K) = 35714.3 ~ 35.7K

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 (tube with loads) will be nearer to 60 (ie: 57-62), depending upon RP and Ro.

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 rp, so also is circuit FREQUENCY response or BANDWIDTH (BW), ie:

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

...where: R = rp||RP||Ro

So, whenever we “swap” tubes, it’s the rp value of the new tube interacting with the RP, Ro, 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 rp' values shown in Table 1 represent preamp tube operation with circuit load resistances of RP = 100K ohms and Ro = 500K ohms, ie:

rp' = (rp||RP||Ro)

The illustrative bandwidth (BW) values shown in Table 1 were calculated using R = rp' and an assumed constant *fictitious* capacitance value of C = 446µF, ie:

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

where: R = rp' and C = 446µF

Table 1 - Preamp tubes sorted by MU values.

TUBE	mu	gm (A/V)	rp(Ω)	Pp(W)	rp'(Ω)	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 rp' value, the lower the bandwidth! Which means that tubes with LOW rp values (and thus circuits with LOW rp' values) will have greater BW and frequency response and proportionately less loss-of-gain (ie: mu') than tubes with HIGH rp values. Table 2 re-orders the preamp tubes listing by their BW, in descending order.

Table 2 - Preamp tubes sorted by BW values.

TUBE	mu	gm (A/V)	rp(Ω)	Pp(W)	rp'(Ω)	mu'	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 "cload" 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 ***infiinite*** **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(f1)- and HIGH(f2)-cutoff frequencies!

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