10.5.9 Tube-strain and -aging

During regular operation, the power tubes of a guitar amplifier become very hot: 250 °C can be easily found at the glass container, and a much higher temperature within it. It is this heat that makes the utilized materials age, that will destroy coatings and consequently deteriorate the operational data. Of course, tubes may also break – but that is not normally the reason for their failure. Common is:

- The cathode coating evaporates from the cathode and deposits on other electrodes; overload accelerates this process.
- An insulating intermediate layer may form on the cathode between the carrier (e.g. nickel) and the emitting layer (mostly barium-oxide).
- Gases released from the electrode metals impair the vacuum.
- Mechanical vibrations bend or destroy electrodes.

In the MOV-datasheet for the GEC-KT-66 we find the lifetime specified at "minimum **8000 hours**". Consequently, an amateur playing 10 h per week at high volume would not need to be worried for 15 years, and even the pro (with 8 h per day of loud playing) would be able to enjoy that set of power tubes for 3 years. Author Helmuth Lemme [1995] quotes entirely different time-spans: he recommends to tentatively change the power tubes after **100 hours**. Edward van Halen apparently acts even more rigorously: allegedly, he has (or had) all power tubes replaced after every gig. Checking the MOV-definition for "end of tube life" more closely, the 8000-hour-euphoria is brought down a peg or two: we find that the output power has gone down to 50% i.e. as long as a 100-W-amp will yield 50 W, the tubes are deemed o.k. A guitar player will hardly be content to work with half the specified power, though, and therefore the MOV-definition is lacking in practical relevance. MOV is silent about the characteristic of the drop in power, we only find that reducing the strain on the tube by 40% will extend the lifetime by 25%. That does not help us to draw any conclusion about the lifetime under overload conditions. The latter often appear in guitar amplifiers; operating outside of the specified ranges is often the case. The recommendation to replace the output tubes after 100 h to check is therefore not entirely without merit. We will happily avoid discussing the occasionally found (wacky) idea that tubes should be "run in" for about 100 hours before they sound right; rather we will opt to clarify the question which operational state puts the highest strain on the tubes.

Just switching on an amplifier can be detrimental: subjecting the still cold tube to the full plate-voltage may cause parts of the cathode-coating to detach. Here, the good old **rectifier tube** did have an advantage: only once it had heated up, the full supply voltage was available, and by that time, the other tubes generally were at operating temperature, too. On the other hand, just keeping the filaments powered up without any current through the cathode should be avoided, as well, because it supports the build-up of the impeding intermediate layer (exceptions are the so-called long-life tubes). Whether an amp should, during breaks in playing, continue to run with the plate-voltage switched on, or switched off (i.e. on standby), or should be powered down completely is discussed controversially. Complete shut-down does reduce the "hours in action", but it brings numerous strong temperature fluctuations that also reduce the tube-lifespan – better leave the power on, then. Regarding the use of the stand-by mode, there are only assumptions: advantages and disadvantages are more or less in balance. In amplifiers with a high-bias current, the stand-by mode can be purposeful because in these amps the tubes are under the highest strain without an input signal. An example would be the VOX AC-30: in idle-mode, the maximum strain on the plate of the EL84 is usually already exceeded – but it is exactly this amp that does not have a stand-by switch.

What does put the strain onto the power tubes? The heating (or even over-heating) of the electrodes! Without a technical-education background, one could assume that the amp being operated at full drive would bring the power tubes to their strain-limit; overdrive would then cause **overload**. That is, however, not correct per se: relevant for the power dissipation at the plate is the product of plate-current and plate voltage. For example: in the idle-state, there are 450 V between plate and cathode[♣], and the bias-current is 40 mA. The plate dissipation then measures 18 W. If the tube can take 30 W, this strain in idle is not critical. As a drive signal is fed to the amp, both U_a and I_a change. The change, however, in opposite directions: as I_a rises, U_a falls. At the drive-limit, the plate dissipation would even converge to zero (at least for idealized conditions): either the tube conducts; in that case there is a plate-current but the voltage drop across the tube is zero. Or the tube is in blocking state; now there is a high voltage across the tube but the current is zero. No power tube is that ideal, though: at maximum plate-current, we find a voltage of about 50 V between plate and cathode, or even more. Still, even with a plate-current of I_a = 0.3 A, this would imply merely 15 W i.e. totally uncritical. The danger lurks in the intermediate range at around half of the drive-level range: $225\text{V} \cdot 0.15\text{A} = 34\,\text{W}$. With a 30-W-tube, we would be already outside of the specified **strain limit**. The latter needs to be seen as an average value, though – the tube is not operated statically in this state for the duration since the input signal changes all the time. Here, we find strain calculations that determine the plate dissipation for sinusoidal drive signals. This is not entirely unreasonable, but not typical, either: the signal delivered by an electric guitar is not sinusoidal. Alternative calculation methods assume a square drive signal and result in a 23% higher strain on the plate – however, the guitar signal is not always of a square shape, either. In any case: even assuming worst-case as continuous operational state, the plate will take on the thermal strain quite nicely – at least as long as the load impedance fits.

But then there's the **screen grid**! Contrary to the situation at the plate, the voltage at the screen grid decreases insignificantly in the presence of a drive signal, therefore it remains an ideal landing spot for the electrons when the plate-voltage is small. Consequently, current and dissipation in the screen grid increase as the plate-voltage drops. Since the maximum allowable dissipation in the screen grid is smaller than the maximum allowable plate-dissipation, the screen grid can easily be made to **glow**. Moreover, it is much more difficult to observe this compared to a glowing plate because the screen grid is surrounded by the plate. Here is a numeric example: the 6L6-GC is specified with $P_{a,max}$ at 30 W and $P_{g2,max}$ at 5 W. At full drive level (U_B = 400 V, U_{g2} = 350 V), the plate experiences a strain of 19 W, and the screen grid of no less than 15 W! Such an extreme overload must only be present for short periods unless we want to run the risk of the screen-grid wires melting and the tube dying. This is why, during the circuit design, the screen-grid dissipation is measured, as well, and measures to limit it are taken if necessary. The tried-and-tested method here is to introduce a **screen-grid resistor** in series with the grid. In fact, this resistor has two functions: to suppress RF-oscillations, and (given the appropriate resistance) to decrease the voltage at the screen grid for high currents through the screen grid. Some old **Marshall-** and **Fender-amplifiers** lack any screen-grid resistor, and the lifetime of the tubes can become extremely short – in particular if the **EL34** is deployed. This tube is a true pentode and the current through the screen grid can easily reach values 2 – 3 times as high compared to the 6L6-GC. If a screen-grid resistor is present, it often is given a value of 1 kΩ. This resistance is recommended as adequate to avoid RF-oscillations, but the screen-grid dissipation may not be reduced enough. You could raise the resistance to 5 kΩ, but that may have effects on the output power and the sound (the latter of course being a matter of taste). Sound or safety – you choose.

[♣] That would be for class-AB operation; for class-A operation, the strain on the tube is highest in idle.

The family of output characteristics gives us a clear overview regarding the relation between current and voltages (**Fig. 10.5.30**). Changing the drive levels shifts the operating point along the load line and changes the power dissipation at the plate. The fact that the load line traverses the power-hyperbola, and that a peak value of 44 W results, is not critical because the operating point advances into the range of such high dissipation only for one half-wave. In the worst case (a square wave-shape), the thermal strain on the tube is 22 W, which is still clearly below the 30-W-limit.

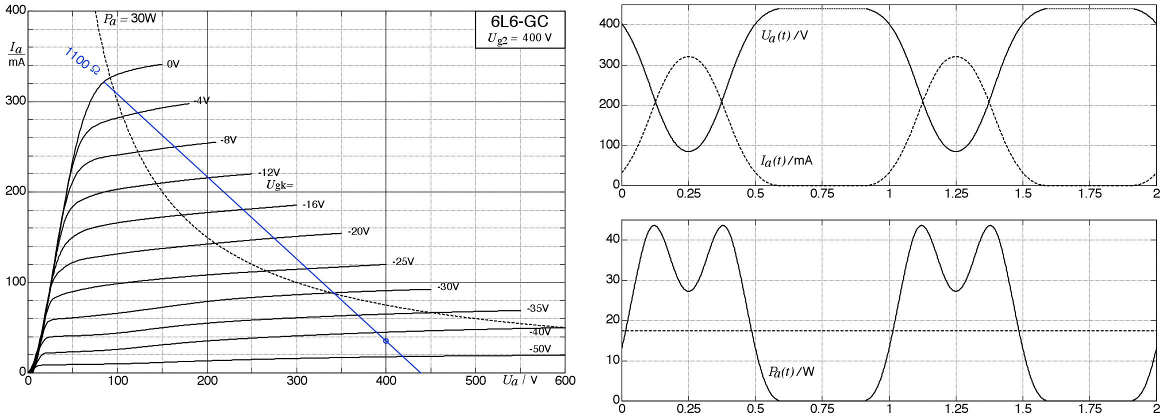

Fig. 10.5.30: family of output characteristics of the 6L6-GC for a load impedance of 1.1 kΩ; time functions for a sinusoidal drive-signal. In a push-pull output-stage including an output transformer, the plate-voltage would not be limited to 440 V (as indicated here) but rise to 700 V (Chapter. 10.5.3).

Fig. 10.5.30 is for a purely ohmic **load-impedance** of 1.1 kΩ. If this value changes, the gradient of the load line changes, as well, and with it the strain on the tubes. Increasing the load-impedance (smaller load-line gradient) reduces both plate-current and dissipation at the plate. Decreasing the load-impedance increases the strain on the plate: a power stage specified for 8 Ω should therefore not be operated at 4 Ω for extended periods of time.

We find entirely different functions for the **current through the screen grid** (**Fig. 10.5.31**). Given a constant voltage at the screen grid, the maximum power dissipation at the screen grid rises to 125 W – if at all, this is only allowable for impulse-operation: according to the datasheet, 8 W should not be exceeded. Even with 1.5 kΩ connected between voltage source (again 350 V) and screen grid, the allowable screen-grid-dissipation is, at 20 W, considerably exceeded. The same holds for the 6L6-GC (**Fig. 10.5.32**). On the other hand, the question remains whether this state can actually happen during real operation?

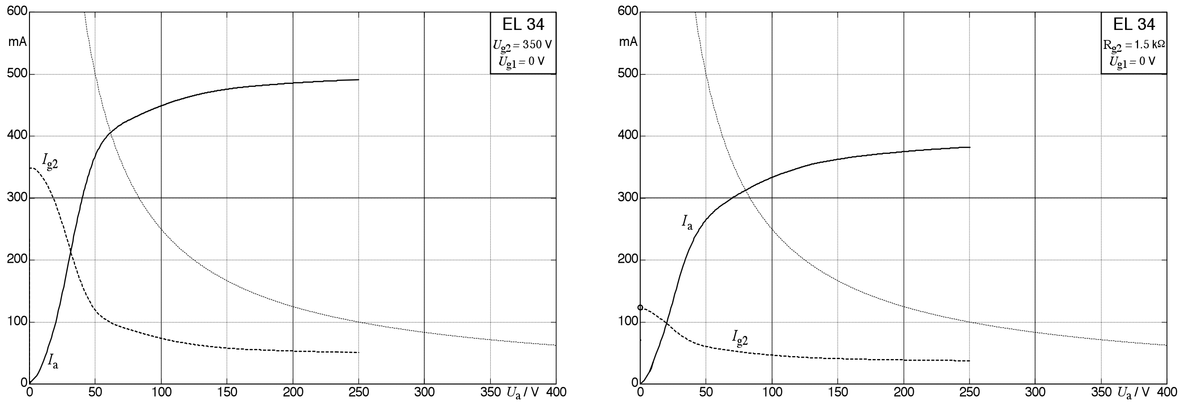

Fig. 10.5.31: Plate- and screen-grid-current dependent on the plate-voltage.

Fig. 10.5.32 depicts the average power dissipation at plate and screen grid, dependent on the drive levels (square-shaped drive signal). The highest plate dissipation P_a appears at $U_{g1,\max}$ = -14 V; for R_a = 1100 Ω the average dissipation is P_a = 22 W, which is safely below the strain limit. A higher load-impedance (1500 Ω) reduces the strain on the plate, and we generally find that **a higher-impedance loads relieve the plate**. The maximum power dissipation at the screen grid P_{g2} happens at $U_{g1,\max}$ = 0 i.e. at a fully overdriven power tube. For a load impedance of 1100 Ω, P_{g2} is 8 W, and for a 1500-Ω-load we already see 14.5 W – three times the allowable power dissipation at the screen grid. For overdrive conditions we therefore find: **higher-impedance loads put more strain on the screen grid**.

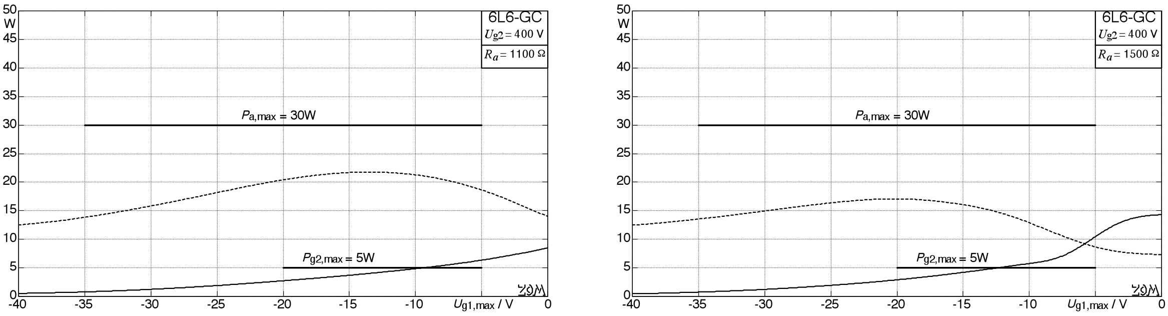

Fig. 10.5.32: Symmetric square-shaped drive around the operating point of 45 V / 30 mA, power dissipation at plate and screen grid (averaged over time). No screen-grid resistor

Consequently, a tube amplifier can in no way be seen as totally immune against a **load-mismatch**. The 8-Ω-output should indeed be connected to an 8-Ω-loudspeaker! Too small a load-impedance (e.g. two 8-Ω-speaker-boxes in parallel = 4 Ω) would increase the strain on the plate – although this would not lead to immediate failure. On one hand, there is some overhead here, and on the other hand, the higher stain will reduce the supply voltage (depending on the power supply circuit) such that the strain is not quite as high. Too high a load-impedance (e.g. a 16–Ω-speaker connected to an 8–Ω-output) will increase the strain on the screen-grid – in particular if the power stage is operated often under overdrive-conditions. In this case, there is little reserve, as everybody measuring the power stage (connected to a loudspeaker) with a sweep may notice right away: every speaker will turn high-impedance at high frequencies, irrespective of its nominal impedance (Chapter 11). With such a high-impedance load, even a single measurement can lead to immediate failure of the power tubes. Looking at the datasheet and considering a load-impedance of double the optimum value, we find a static power dissipation at the screen grid of 40 W: P_{g2} = 0.1 A · 400 V (at U_{g1} = 0 V). The tube is in active state during only one half-wave such that on average 20 W remain, but that is still much too high compared to the allowable max. 5 Watt. Also, the speaker impedance may not merely double – a 10-fold increase is possible, as well.

In view of all this, the impression manifests itself that the classic power-stage circuits were not developed for Hardrock but for radio programs. And indeed, how could it be otherwise: 70 years ago, the place of action for a 6L6 was a radio receiver in most cases (or maybe an amplifier in a cinema, at most). Guitar amplifiers were few and far between. Even if such a tube found its way into such an exotic job site, it still lived a relatively tranquil life – the rocker "turning everything to 10" was only just about to be born. He (or she) arrived only later, but then used amplifiers that were – with unbelievable tenacity (or ignorance) – built as if reproducing moderate dance music without distortion were the only way of life. Marshall model 1987 amps of certain vintage include two EL34 but no screen-grid resistors. Lucky are those who can after each gig afford a new set of tubes (at 50 to 100 Euro).

We can insinuate that the developers of the early “original circuits” strove to avoid overloading the tubes too much at least in idle mode. No guitar player will buy an amp for its idle-mode qualities, though, and will “turn it up” at some point. Several parameters determine how the strain on the tubes will then change: the drive levels, the loudspeaker impedance, the specific tubes used, and the circuit variant. To start with the latter aspect: most amplifier circuits went through a number of stages of advancement, often driven by the demand for more power. When the Fender Twin entered the market in 1952, it was specified at 18 W. Only 3 years later, this power output had grown to 30 W, then 60 W and 80 W, and finally to 100 W (and beyond). The 5C8-Twin feeds 370 V to the plates – in the AC568 this is 470 V. A VOX AC-30 expects its EL84 to each put up with 14 W in idle, if it is operated with the rectifier tube customary back in the early days. Exchanging the rectifier tube for silicon diodes (a design development in later AC-30’s) pushes the power dissipation at the plates to 17 W each. Marshall amps may or may not sport screen-grid resistors (25 Ω, or 470 Ω, or 1 kΩ), and the tube complement could include KT-66, 6L6-GC, EL-34, KT-88 or 6550. Therefore even if amps look similar, the strain on the tubes may differ significantly.

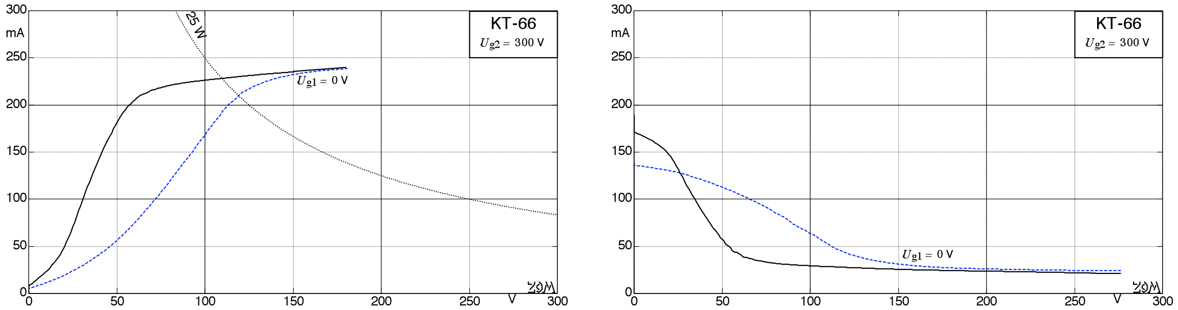

Fig. 10.5.33: Characteristics of two tubes both sold as KT-66; plate-current (left), screen-grid current (right).

Occasionally, even the tube designations may be just as unspecific: the measurements shown in **Fig. 10.5.33** were taken from two fresh KT-66. They show significant differences both in the achievable maximum output power of the amplifier, and in the strain on the tubes, despite the fact that allegedly this is the same type of tube. To be sure, most tubes sold today will be roughly in the ballpark of the datasheet specifications; however, the amount of deliberately sold “selected” defectives unfortunately is not petty – to put it mildly.

It requires no emphasizing that the strain on the tubes depends on the speaker impedance, too: loudspeaker impedances are complex and strongly dependent on frequency (Chapter 11.2), and therefore the load line deforms into an ellipse in real operation, rendering immaterial all calculations of power dissipation for nominal load. In addition, the input signals almost never correspond to the textbook-sinusoidal shape: power stages in guitar amps are often overdriven. Not always, admittedly – but even with a seemingly “clean” sound, the string attack can drive the power stage into short-term limiting. More than a few guitarists appreciate their tube amps especially because of the power-stage limiting which is not easily imitated via small effects boxes (in contrast to the pre-amplifier distortion). Under overdrive conditions, a current flows through the control grid polarizing the coupling capacitors such that the operating point drifts back and forth depending on the drive signal – not an effect that is typically discussed in circuit-design textbooks. The latter will give you guidance to push the THD below 1%, and will exemplarily calculate the whole HiFi power stage. Continuous overdrive is not a topic here, nor was it in 1940 for the amp-forefathers. Only today, in everyday stage-life, it very much is.

In order not to succumb to the temptation to join in and explain the operating characteristics of a guitar amp only in the linear range, let's turn to 10 now – proud 'n' loud. The candidate for our measurements is a Fender Super-Reverb, its two 6L6-GC generating an output power of approximately 40 W – or more if we go into overdrive. Which we do: **Fig. 10.5.34**.

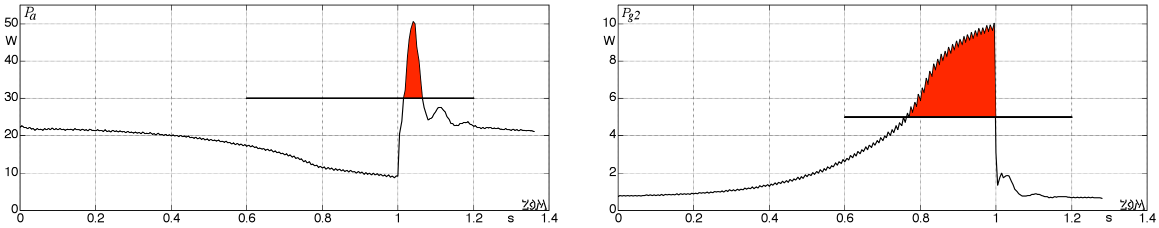

Fig. 10.5.34: Average power dissipation at plate and screen grid of a 6L6-GC, Super-Reverb. I_{Bias} = 50 mA. Sinusoidal 1-kHz-tone with a level increasing by 20 dB from 0 – 1 s; switch-off at $t = 1$ s. Measurements taken with 8 Ω load (purely ohmic) for plate dissipation, and 16 Ω load (purely ohmic) for screen-grid dissipation.

The drive signal is a sine-tone with a level increasing by 20 dB from the time "0" to the time "1 s"; at $t = 1$ s we switch it off. During the last quarter of the measurement, the power stage is overdriven, which does not harm the **plate** at all: its strain decreases to about 10 W with increasing drive level. After (!) switching-off, however, there is a short-term plate dissipation of 50 W due to the settling of the polarization of the coupling capacitors. The tube does not die right away because this overload happens only for a short time. If such short-term overload conditions repeat themselves quickly one after the other, they could, however, pose a problem, after all. Also, 50 W is not really the end of the line: corresponding measurements with a real loudspeaker as a load resulted in more than 100 W!

We see a rather different behavior for the power dissipation in the screen grid: it grows with increasing drive level, and approximately at the point where overdrive occurs it crosses over beyond the maximum value of 5 W. Therefore: as soon as the power stage is overdriven, the **screen grid** enters the danger-zone. If we could address one of the design-forefathers with this problem, the answer would probably be: "you don't overdrive the power stage!" Yeah you do, these days. The argument that the Super-Reverb is an amp for rhythm-guitar that should be played "clean" could easily be countered in that the power-stage design for this amp corresponds to the Fender-standard of the 1960's – the power stage of the Bassman (as just one example) is in no way more less prone to be overdriven. This was all by-the-book design. At the time.

Overdrive is the joint cause for putting excessive strain on plate and screen grid; the exact effective mechanisms are specific to the respective electrode. Normally, the plate-voltage in a power tube decreases with increasing plate-current; at full drive level ($U_{g1} = 0$), the plate-voltage will be minimal. At this point, however, the plate becomes rather unattractive as a landing-site for the electrons (emitted by the cathode). The electrons are much more attracted to the screen grid that remains at a high potential (high voltage), and they land (at full drive level) on the thin screen-grid wires. The latter promptly heat up under this bombardment and start to glow. Even datasheets do not shy away from specifying a power dissipation of 100 W or more for the screen grid (at $U_a = 0$) – and at the same time they will give a maximum strain of 5 W. This is not a contradiction, because for short-term strain (impulses), the dissipation limit is higher. How high is not specified, unfortunately. At the plate, entirely different processes are significant: as long as the load-impedance of the power stage is not too low, the plate does not run into danger even under dramatic overdrive conditions. However, the coupling capacitors will vary their average DC-voltage during periods of overdrive, and during the following balancing processes, danger looms, after all.

The source for the balancing processes just mentioned is the phase-inverter (Chapter 10.4). The two signals generated by the phase-inverter are equal in magnitude and opposite in phase only for moderate drive levels. Strong drive levels shift the operating points in the phase-inverter, and the coupling capacitors change their average DC-voltage. As the input signal is switched off, the coupling-capacitors potentials return to their quiescent state within 2 s[♣] – it is here that the peaks in the power-tube-specific strain occur.

Another problem may present itself at the fringes of the transmission range: at very high and very low frequencies, the two signals from the phase-inverter do not maintain exact opposite phases. The output transformer can generate its impedance-transforming magnetic field only in an efficient manner if the plate-currents support each other. If both power tubes conduct at the same time, the transformer has the effect of a bifilarly wound coil – with the effect that the inductance goes to zero, and merely the copper resistance of the primary winding remains as load impedance for the plate (e.g. 50 Ω): the plate will possibly be overloaded.

In **Fig. 10.5.35** we see once more the family of output characteristic of the 6L6-GC, with an I_a/U_a-characteristic measured for a JJ-6L6-GC. For a load impedance of 1200 Ω, the "knee" of the curve is almost exactly met; the strain on the screen grid at this point is 350 V · 46 mA = 16 W. As we increase the load impedance to 6000 Ω, the strain on the screen grid grows to 54 W. Assuming that this maximum strain occurs only during one half-wave, we may half that value – but the remaining 27 W still overshoot the allowable maximum value considerably. The approximate load-impedance for the specified match is 1200 Ω, i.e. 8 Ω for the Super-Reverb[2]. However, loudspeaker measurements show that the magnitude of the speaker-impedance will be larger that than the specified impedance both at high frequencies and at the speaker resonance. A primary load of 6000 Ω corresponds to a secondary load impedance of 40 Ω – this can easily be achieved with a loudspeaker. A guitar will not normally generate continuous tones at 15 kHz, but sustaining notes in the range of the speaker resonance are possible – and may be dangerous.

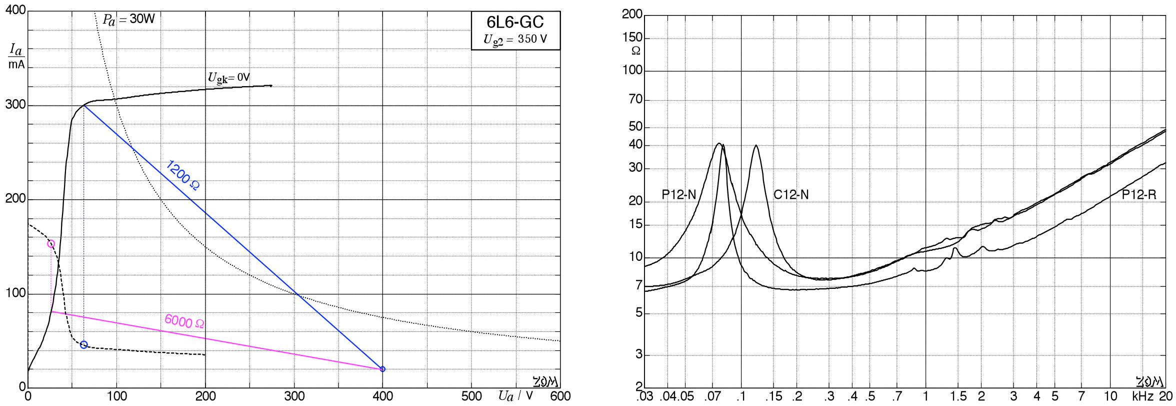

Fig. 10.5.35: output characteristic of a 6L6-GC (JJ) for two different loads on the plate (left), loudspeaker impedances (Jensen, right), plate-current (——) and screen-grid-current (---) for $U_{g1} = 0$.

In order to remain datasheet-compliant, the screen-grid resistor in Fig. 10.5.35 is assumed to be 0; in return, the screen-grid-voltage is only set to 350 V. A Fender-typical resistor-value would be 470 Ω, connected to 400 – 450 V. As a first-order approximation, we find similar strains on the screen grid; in the detail, there are differences that however cannot be calculated to the last watt.

[♣] In theory, this asymptotic recharging takes an infinite time; 2 s should be seen as a specific guidance value.

[2] As already mentioned, this specific Super-Reverb carried a transformer with both 2-Ω and 8-Ω-outputs.

Often, the screen-grid resistors are connected to the first or second filter capacitors in the power supply. Without any signal at the amplifier input, these electrolytic capacitors charge to 400 – 450 V; with a strong input signal this voltage drops a bit (sags). How much the voltage drops depends on the load impedance and the internal impedance of the power supply. The sagging effect will be stronger for power supplies with a rectifier tube, and weaker for ones with silicon diodes. A power supply with rectifier tube and small caps (10 µF) will go easy on the screen grid while silicon diodes and 100 µF represent a challenge. Unfortunately, the datasheets for usual power tubes do not reveal any thermal time-constants of the screen grids, and therefore any calculation of the impulse-strain will remain speculative. Only with the triumph (?) of power transistors, impulse-diagrams enter the datasheets. The 2N3055 (aka BD-130), for example, is specified with 100 W continuous power dissipation at 20°C of the casing, with 320 W for 1 ms, and even with no less than 900 W for 30 µs. For the 6L6-GC, we find 5 W as a limit-value for the screen grid power dissipation, without any further details. In the semiconductor area, there is at least a rough guideline (in case you want to avoid much calculation) that the lifespan doubles if the operating temperature is decreased by 10°C. Given tubes, we need to rely on completely flaky speculations. How long did that Mullard survive 100% overload at the screen grid, and how does its modern Chinese remake fare? The remake that raises the suspicion that it's mostly the cosmetics that is important (it's got the brown base!). Caution, though! With such prejudice, you may well do very wrong by those sino-factures. Not everything that originates in China is bad – just as is the case for any other country. As he developed the 5881, was the Tungsol-R&D-guy in the US really interested in how strongly the screen grid would be overloaded in guitar amplifiers, and was that tube therefore marketed as the "better 6L6"? As late as 1962, the Tungsol datasheet specified: "*Maximum Grid #2 Dissipation: 3 Watts*". That's not really a lot, either, isn't it?

These days, acquiring a hand-wired boutique amp will easily set you back 4000 or 5000 Euro. That's without speaker, of course. Maybe the manufacturer boasts using only output transformers with original insulation-paper (with worse breakdown rating) and slightly rusted transformer sheets – to get the 'brown' sound? Maybe he will put a 1-A-fuse in the mains line (just as in the original) without realizing that converting from 110V to 220V the value of the fuse should be halved? It all has to be *original*- that's the main thing. Or, the focus is on using the same circuit that made the Bassman (or the Deluxe, the Twin, the JTM – you name it) famous. Including all the grid-destroying characteristics of these old amps. Amazing how the oldest cows are the most holy ones. Maybe it was the CBS-engineers who, by introducing protective circuits, discredited just these circuits. A guitar amp sounds best if it gobbles up a set of power tubes each evening – it's a cast-iron credo.

Rating Systems [Langford-Smith & RCA-Receiving-Tube-Manual]**:**
The **absolute maximum system** originated in the early days of valve development and was based on the voltage characteristics of battery supplies. Battery voltages could fall below their nominal values but seldom appreciably exceeded them, so that valve maximum ratings set on the basis of specified battery voltages were absolute maximum ratings that should not be exceeded under any condition of operation.
The **design center system** was adopted in the U.S.A. by the Radio Manufacturers Association in 1939 for the rating of receiving valves and since then has become the standard system for rating most receiver types of American design. Under the design center system, ratings are based on the normal voltage variations which are representative of those experienced with […] power lines. Design center ratings should not be exceeded under normal operation. These ratings allow for normal variations in both tube characteristics and operating conditions.
The **design maximum system** was adopted for receiving tubes in 1957. Design maximum ratings should not be exceeded under any condition of operation. These ratings allow for normal variations in tube characteristics, but do not provide for variations in operating conditions.