Circuit Description for the Dynaco Stereo 120 Power Supply

INTRODUCTION

This paper describes the circuit for the Stereo 120's power supply. At the end of this paper, we've collected some FAQs that may help you trouble shoot your supply if there's a problem.

The power supply design stuffs a lot of functionality built into a very few semiconductor devices. Today, we'd probably use a few more devices, or an IC to get all this done. A few things, most notably the current limit of this supply, are a bit sloppy. Still, it's interesting to see how much can be done with so little.

The power supply's behavior depends upon the load current, the voltage on C9 (the main rectifier filter), C12 (the output filter), and C10. As noted before, the power supply is a very clever design, squeezing a lot of functionality out of a few transistors. Those functions include:

1. Slow Start
2. Voltage Regulation
3. Current Limiting and Foldback

We'll investigate the startup sequence. Starting with all the capacitors uncharged, we'll analyze the power supply's various operating modes as the capacitors charge up. Then we'll investigate its behavior during normal operation, when the load transitions from a normal load to one that's too heavy.

STARTUP SEQUENCE

Charging C9

When power is applied, C9 charges through the transformer and diode-bridge (D4-D7) to a DC voltage of around 93 Volts. If it charged completely on the first cycle starting from a zero crossing, it would take a peak capacitor current of:

$$Ipeak = 93 \cdot 2 \cdot \pi \cdot 60 \cdot 1000 \cdot 10^{-6} = 35 \text{ Amps}$$

The current can be even higher if you happen to turn the amp on near a peak of the AC line. It is those large currents that cause the "bong" sound as you apply power to the amp. In practice, the peak currents are diminished by transformer winding resistance and leakage inductance. Still, it's probably safe to assume that C9 reaches full voltage within 2 cycles of the AC line, or 33 milliseconds, as this represents 4 charging cycles owing to the full wave bridge rectifier. The main point of this discussion is that C9, the input filter capacitor, charges up much faster than C12, the output filter capacitor.

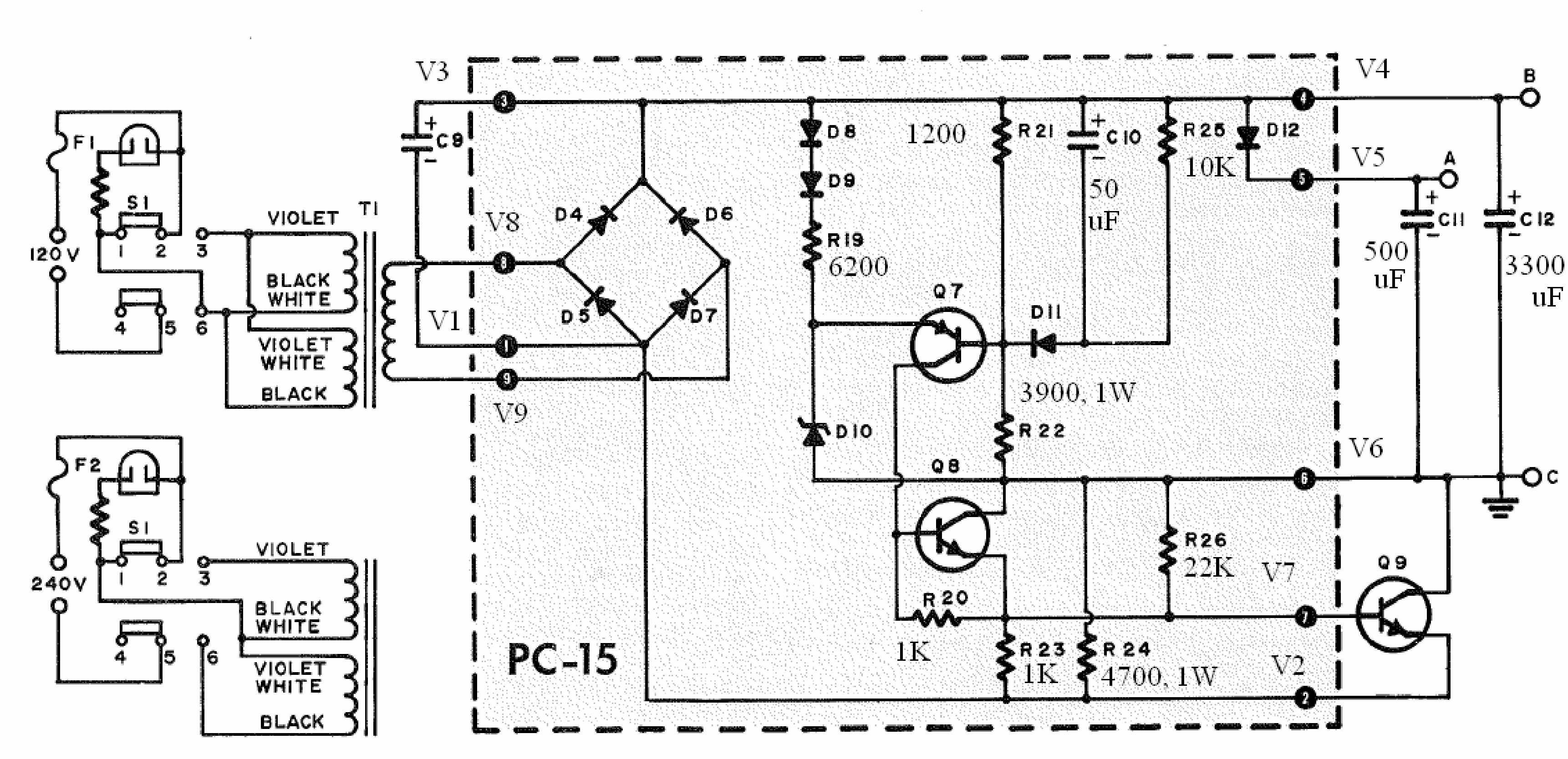

Figure 1 – Schematic of Dynaco Stereo 120 Power Supply

Charging C12 (Current Limited)

We assume that C9 reaches full voltage before C12 has done very much charging. Let's investigate C12's charging behavior in the current limited phase:

- V4≈0 (C12 is initially uncharged)
- V2≈-93 (C9 has reached full voltage)
- Q7 is off (with V4≈0 there's no voltage to run it)
- Q8 is off (with no current in Q7, there's no base drive for Q8)

If we remove all the stuff that's essentially not there owing to it being turned off, we arrive at Figure 2. This is a much simplified schematic of the power supply applicable in the current limited phase of turn-on.

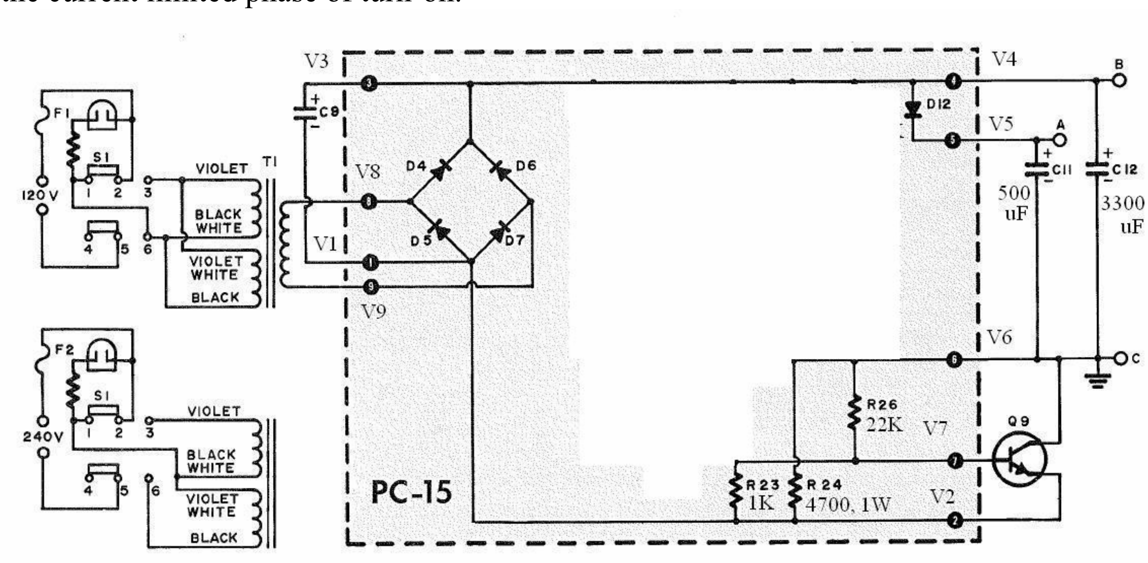

Figure 2 – power supply equivalent circuit during charging phase of turn-on

The charging paths for C12 are:

- R26 in series with R23
- R24
- Q9, as turned on by R26 and R23

The last charging path is the most interesting. Q9, R24, and R26 form a structure known as a Vbe multiplier. In this circuit, Q9 conducts so long as:

$$Vce(Q9) > Vbeon(Q9) \cdot \left(1 + \frac{R26}{R23}\right) \approx 0.6 \cdot (1 + 22) = 13.8 \text{ Volts}$$

This is definitely true at startup, since Vce(Q9)=93 Volts. There is a current limiting effect however, due to Q9's finite β. I'll skip the derivation, but during the charging time, R24, Q9, R26, and R23 have the equivalent circuit shown in Figure 3, where:

$$Rqe \approx \frac{R26}{\beta(Q9)} = \frac{22000}{37.5} = 587$$

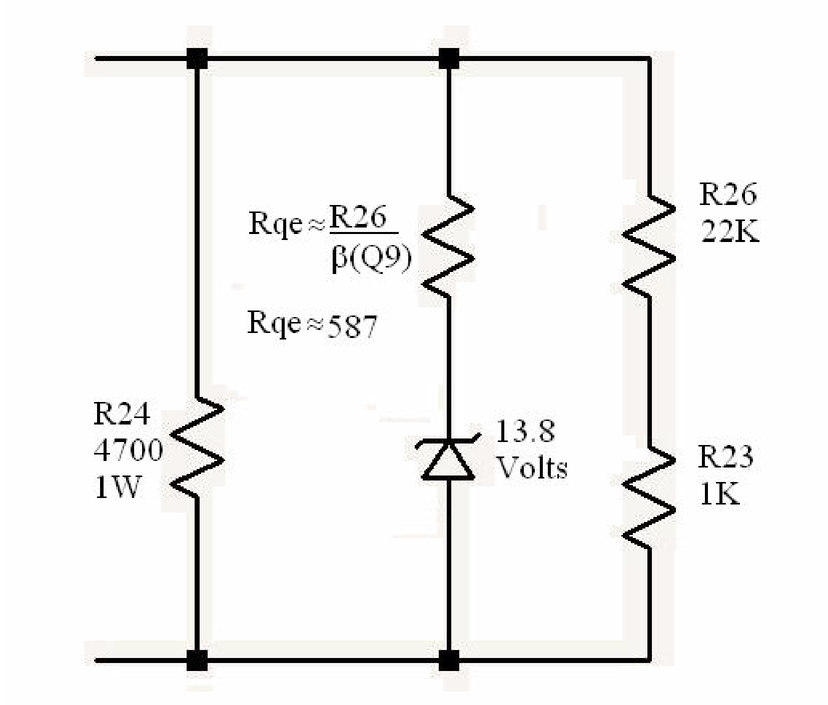

Figure 3 – equivalent sub-circuit during charging

We note two things:
1. Q9 is the most significant charging path
2. The charging current depends on Q9's β

This is one of the reasons why the parts list shows a beta range of 25-50 for Q9. The other reason will show up when we do current limiting calculations. The time constant for the charging of C12 is approximately the product of 500 Ohms[1] and 3800 uF (C11 and C12 in parallel), or about 1.9 seconds.

<u>Charging C12 (Q7 and Q8 Turn On)</u>

Eventually, enough voltage appears across C12 that Q7 turns on, turning on Q8, further turning on Q9. This increases the speed with which C12 charges. Let's now investigate when Q7 and Q8 turn on.

C10 charges with a 40 millisecond time constant, much faster than the 1.9 second time constant of the driving voltage. Therefore, we can ignore C10 in this analysis. There isn't enough voltage to turn D10 (a 58 Volt zener diode) on yet, so it is effectively out of the circuit. Q8 turns on once we get a Vbe(on) across R20. This happens when Q7 has a collector current of 600 uA. At that point, R19 has a voltage of 6200*0.6e-3=3.72 Volts, making Q7's emitter 3.72+0.6+0.6=4.92 Volts below V4. To turn on Q7, its base must be 5.52 Volts below V4. That makes the following currents:

[1] A convenient rounding of the 587 Ohms and parallel charging paths.

$I(R21) = \dfrac{5.52}{1200} = 4.6$ mA, and $I(R25) = \dfrac{5.52-0.6}{10000} = 0.492$ mA. This makes the current in R22 4.6+0.492=5.092 mA, and the voltage across R22 is 3900*5.092mA=19.86 Volts. Adding the 19.86 Volts with the 5.52 Volts gives us V4=25.37 Volts when Q7 starts to turn on. If you check the result with simulation, it's consistent to within the level that the Vbe=0.6 approximation would allow.

Once Q7 and Q8 turn on, there's drive for Q9, and V4 rises more quickly. The next phase of operation occurs when V4 is large enough that D10 turns on preventing any further rise of Q7's emitter voltage, entering the regulated mode of operation.

Entering Regulation

V4 starts to enter regulation when it's high enough to supply Q7's emitter current (at least 600 uA) and keep D10 alive (well say that's another 100 uA). This gives us:

$$V4 > 58 + 6200 \cdot 0.7 \cdot 10^{-3} + 0.6 + 0.6 = 63.54 \text{ Volts}$$

With 58 Volts on Q7's emitter, we'd be completely in regulation. However, until V4 reaches its final value (around 72 V), the base of Q7 is low enough to cause more current to flow in Q7. This keeps the output voltage, V4, rising.

For example, when V4=64 volts, ignoring D11, the voltage on the Q7's base is $V(Q7base) = 64 \cdot \dfrac{3900}{3900 + 1200 \,||\, 10000} = 50.2$ Volts. That's low enough to turn on Q7 quite a lot, which raises the output voltage, V4.

V4 stops rising when the base of Q7 rises to 58-0.6=57.4 Volts. When that happens, the current in R22 is:

$$I(R22) = \frac{57.4}{3900} = 14.71 \text{ mA}$$

That current must be supplied through R21 and R25-D11. That says:

$$\frac{V4-57.4}{1200} + \frac{V4-57.4-0.6}{10000} = 14.71 \cdot 10^{-3}.$$

Solving for V4, we get 73.21 volts, pretty close to the nominal 72.[2]

[2] We neglected Q7's base current, and approximated the zener voltage and Vbes.

PROTECTION OPERATIONS

If the power supply sees too heavy a load, it shuts down to protect itself. This section describes what happens.

Maximum Output Current

The power supply remains in regulation so long as D10 has some current going through it. As the load on the power supply increases, Q7 steals current from D10. To find the largest output current that remains within regulation, we'll assume Q7's emitter is at 58 Volts, but no current flows through D10. Q7's emitter current is then about $Ie(Q7) = \frac{72-58-0.6-0.6}{6200} = 2.06$ mA. This current feeds the base of Q8 and R20. R20 takes 650 uA (assumes that Vbe(Q8)=0.65 at the elevated collector current associated with the high output load. That leaves 2.06-0.6=1.46 mA for Q8's base current. That produces 120 times as much current in Q8's collector[3], or 175 mA. That becomes base current for Q9. Multiplying by β(Q9), we get 0.175*37.5=6.56 Amps, the output current limit of the power supply.

Essentially, the current limit in Amps is about[4]:

$$\beta(Q8)\cdot\beta(Q9)\cdot 0.0014 \approx 120\cdot 37.5\cdot 0.0014 = 6.3\,Amps$$

Note that the maximum power supply current isn't that well controlled. It depends on the product of β(Q8) and β(Q9). Both of those depend upon what transistors you begin with, and the temperature at which they're running. When Q8 and Q9 get hot, their betas increase. This current limit is therefore rather sloppy. If we consider the range of β specified for Q8 and Q9 and ignore temperature, then the current limit ranges from 3.5 Amps to 9.8 Amps![5] In practice, it probably won't get that high because Q9's β falls off at high currents.

Overload Currents

If the load pulls more than the maximum current, the output voltage starts to sag. This makes even less current available via D8-D9-R19. That makes even less current available, so the output sags even faster. This is a positive feedback situation that eventually cuts off Q7 and Q8, leaving just R23, R24, and R26 to try and restart the power supply. That says that we have about a 500 Ohm resistor in series with the very heavy load, limiting the current to about 90/500=186 mA.

When the overload condition is cleared, the limited current will be adequate to create an output voltage high enough to start regeneration, turning the power supply back on again.

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[3] We're taking the middle of the β range shown for Q8.
[4] This slightly lower number is because we rounded down the 1.46 mA to 1.4 mA.
[5] The low limit comes from 0.0014*100*25, the high limit from 0.0014*140*50.

FAQS ABOUT THE POWER SUPPLY

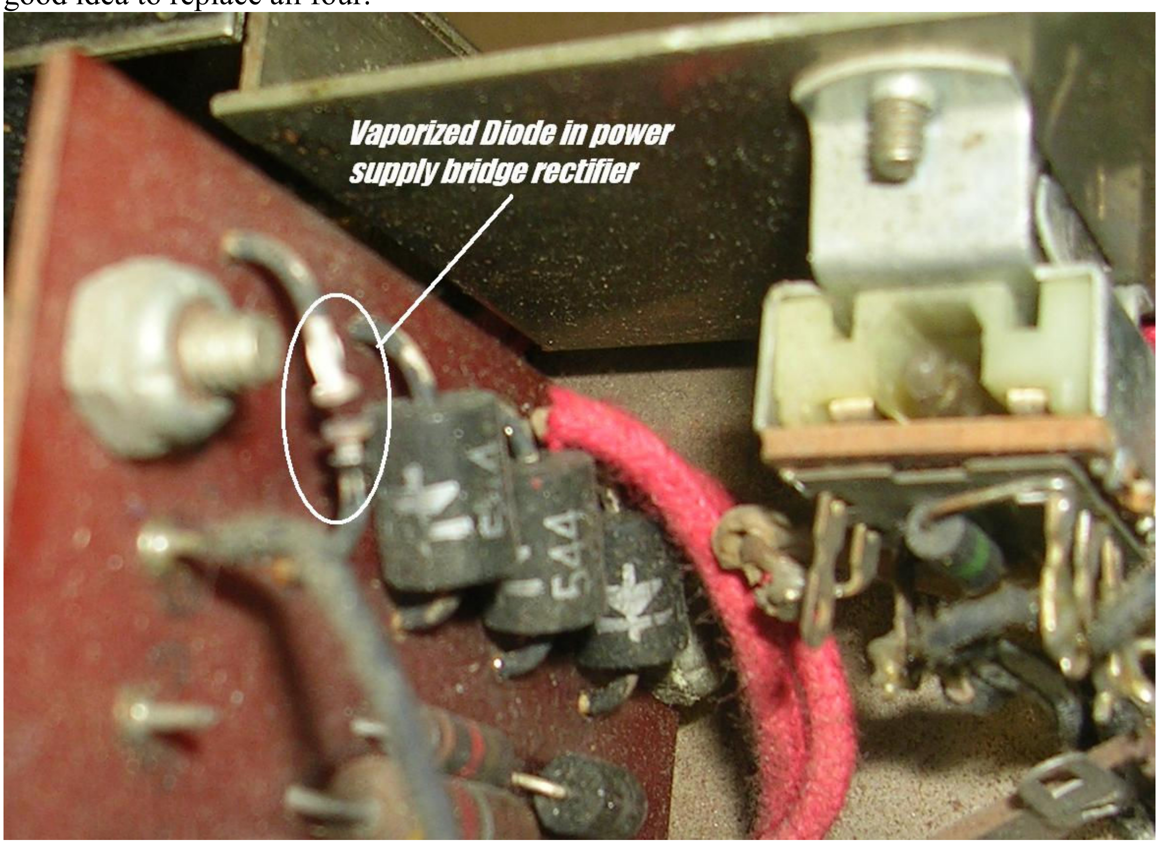
Q. My power transformer hums, more than I think it should...I mean, in the speaker, there's really no hum, but I hear the mechanical hum from the transformer. Is this normal?

A. There will be a little mechanical hum, but if there's too much, there are a couple things to check:

1. did the feet rot off? If the amp is sitting metal to wood on your shelf, the transformer vibration couples efficiently to the wood, making the hum quite audible. If so, replace the feet.

2. It's very likely that one (or more) of the diodes in the bridge rectifier has died. If just one diode dies, the other three still produce reasonable output voltage, but the current to the filter comes at a ripple rate of just 60 Hertz, not 120 Hz. That causes the transformer to take a bunch of unbalance current, making the transformer hum. Find, test, and replace the bad diode(s) in the bridge. You may have to lift one leg of each diode to get an accurate test of each diode.

Hint: if you see one obviously destroyed diode, there's probably another dead diode in the bridge. Given that these diodes may be approaching their 50th birthday, it might be a good idea to replace all four.



Radio Shack sells a 3A 400 PIV diode that works just fine for this application. The original diodes had a 200 PIV rating, but that always seemed a bit marginal to me.

So...check all your diodes, D4-D7, if your transformer is humming more than you think it should.

Q. The fuse blows as soon as I plug the amplifier in and turn on the power. What should I do?
A. Remember to be safe. There's high voltages and currents available in the amplifier. They can be lethal, or just painful, if your aren't careful.

We'll assume that you're installing the updated amplifier modules, and that you've removed the original amplifier modules. That removes short circuits in the amplifier modules as a potential problem. The most likely causes are:

1. shorted diodes in the bridge (D4, D5, D6 or D7). Examine the diodes for damage. Often when they are shorted, the plastic case blows off the diode. Replace all four diodes, even if you seen only one damaged diode.
2. shorted filter capacitors, C9, C11, or C12.
    a. To eliminate C11 and C12 as the problem, disconnect the red wire that goes from PC-15 (power supply PC board) to PC-15, terminal 4.
        i. If the fuse still blows, then either C9 or some of the diodes in the diode bridge are shorted[6].
        ii. If the fuse doesn't blow, then either C11 or C12 are shorted.
    b. To eliminate C9 as a problem, power down the amplifier, disconnect and test C9 for the presence of a short circuit. See the next FAQ for the method.

Q. How do I test a capacitor for a short circuit?
A. Remove the capacitor from the circuit. Be careful, if it isn't shorted, it might be holding a charge. Measure the capacitor voltage with a meter. If there are a few volts, it's probably just fine. If you measure little or no voltage, then the capacitor is probably shorted. Measure its resistance with an ohm-meter. If the capacitor is good, its measured resistance will increase with time. If the capacitor is bad, its measured resistance will measure 1K Ohm or less.

Q. The power supply goes into protection mode, even though the load isn't excessive. What's going on, and how can I troubleshoot it?
A. I just had one of these, and it was a bit annoying until I figured it out. When things were working, D9 would have 0.52 volts across it (pretty reasonable for a low current through a big diode). When the supply went into protection mode, even though the power supply load was not excessive, that same diode had about 8 volts in a forward biased direction across it and a small current through it. Diodes shouldn't behave that way, so I replaced D9 with a 1N4004, and for good measure, I reflowed the solder on the trace that connects D8 and D9. That solved the problem.

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[6] If you're really unlucky, you may find that C11 and or C12 are also shorted, along with C9, and some diodes in the bridge. It's hard to imagine that much bad luck at one time, but some folks are "lucky". It's best to test each of the capacitors for shorts once they are disconnected from the circuit.

Q. Can you make a troubleshooting flowchart for power supply problems?
A. Yes, I think I can, but it's getting late now. I'll put it on my list of things to do. Here's a sketch to hold you over until then. If the load current is reasonably low (assuming original Dynaco amps, this means less than output voltage V4/300, and the power supply output voltage is less than about 30 Volts, then I'd be suspicious about Q9, R23, R24, and R26. If the current is within bounds (I<V4/300), and V4>30 volts, then there's probably no base drive for Q8. Measure the voltage across R19, it should be at least 3 Volts, or the power supply won't start. Similarly, the voltage across R20, it should be at least 0.5 volts, or the power supply won't start. OK, I really have to go to sleep now.

Q. Why are the feedback resistors, R21, R22, and R25 so low? Q7 only has about 2 mA of collector current, so its base current is only about 20 uA. The variation in base current of Q7 could be at most 20 uA, and that would only make about 20 millivolts of difference in the output voltage. That's much less than the 5% resistor tolerance would cause.
A. Remember, these guys were making every component do lots of stuff. These three resistors put a minimum load on the power supply output. This keeps the unloaded power supply output voltage below 75 volts with 93 volts of DC input. That's close enough to the nominal 72 V output that nothing gets over-stressed.

Q. The power supply output voltage isn't right at 72 Volts. It's a little bit high. Is that typical? Can it be dropped to 72 Volts easily?
A. I haven't kept meticulous records, but I've probably seen more power supplies where Vout>72. If you want to drop it back to 72 Volts, it's not hard. Place a resistor in parallel with R21. The easiest way to find the value is to use a resistor substitution box. The value you find will be (most likely) between 1K and 10K Ohms. Don't drop the voltage below 70 Volts, or you may cause the power supply to protect at too small a load current.