Single-Ended
“Big Iron”
Guitar Amplifier

Ray Lyons

An Independent Study Project
at the University of Illinois
with Prof. Steve Errede

When I first started playing guitar, I was unaware of the differences that existed between solid-state and vacuum tube amplifiers. Somewhere along the line, I heard a tube amplifier side-by-side with a solid-state one and my ears have never been the same since. Because of their high price tags, I have not had the opportunity to own a tube amplifier, but when the opportunity arose to build one for a course at the University of Illinois, I seized it. The report that follows will explain the design, construction, and results of a tube amp I created with the priceless assistance of Professor Steve Errede.

Design:

In looking for a tube amplifier to build for this course, I had very little experience working with tubes so I started looking at some of the original designs from Fender and Gibson. What I decided on was to build a single-ended Fender 5F2-A Princeton Amp with the resistor and capacitor values from a 1957 Gibson GA-5 Skylark Amp. Historically, these early amps had smaller output transformers that saturated magnetically when the amp was fully turned up – giving nasty, harsh, buzzy distortion, and also did not maximize transfer of power from the tubes to the speaker load, so I decided to change another factor and build my amp with Hi-Fi Audio quality transformers, many times bigger than the original transformers used by Fender and/or Gibson.

After doing some research online I purchased my transformers from Handwound Transformers [www.HandwoundTransformers.com]. To my knowledge, these transformers are handmade by the owner David Lucas. He uses the "highest quality USA materials" to offer excellent transformers for very reasonable prices.

The power transformer I chose was a 600V center-tapped transformer that is rated to deliver 300V_{AC}(rms) at 200 milliamps (DC), 6.3V_{AC}(rms) at 6.0 amps, and 5.0V_{AC}(rms) at 3.0 amps. This power transformer was chosen to deliver the desired voltage to the power tube plates and also is able to supply enough filament power so that any (popular) combination of rectifier, preamp, and power tubes can be (safely) used in this amp! For the output transformer, I chose a 25 Watt rated 5,000 ? primary impedance transformer with (interleaved) 4, 8, and 16 ? secondary outputs, thereby enabling any (popular) choice of speaker load. The frequency response of the output transformer is supposed to be flat from 10 – 55,000 Hz, which is more than adequate for a guitar amplifier.

When the transformers arrived, I was surprised at how heavy and large they were, and they seemed to be put together very well. In order to gain some insight into why my amplifier would sound different, and arguably better, than the original Fender Champ amplifier we can analyze the differences in the output transformers. Measurements were made on the output transformer being used in my amp from Handwound Transformers and the same measurements were made on an output transformer from a 1968 Fender Silverface Champ (Fender part #022905) as well as a Champ-type output transformer from Angela Instruments. The secondary winding on the Fender output transformer is 4 ? and the secondary winding on the Angela Instruments transformer is 8 ? . For purposes of comparison, the tables below compare the respective winding on the Handwound Transformer's secondary side with the Fender and Angela Instruments transformers.

The measurements (summarize in the below) were made with a Hewlett-Packard HP-4262A LCR meter at 1 kHz. The Primary Load Impedance was calculated two ways. The first way uses Equation 1 below:

Equation 1

$$Z_{Load}^{pri} = \left(\frac{L_{OC}^{pri}}{L_{OC}^{\sec}} \right) \times Z_{Load}^{\sec}$$

Equation 1 shows that the impedance of the transformer is proportional to the ratio of the open circuit inductance of the transformer. The Primary Load Impedance can also be calculated by using a function generator to generate an AC signal (these measurements use a voltage of 10 V RMS) and apply it to the primary winding. The voltage can then be read across the secondary winding and the following equation can be used to calculate the Primary Load Impedance.

Equation 2

$$Z_{Load}^{pri} = \left(\frac{V^{pri}}{V^{\sec}} \right) \times Z_{Load}^{\sec}$$

In the tables below, SC and OC stand for Short Circuit and Open Circuit, respectively. The SC/OC notation applies to the opposite-side configuration. For example, in the first measurement of Primary Open Circuit Inductance ("Pri. OC Inductance"), the Inductance was measured across the primary winding, while the secondary winding was an open-circuited. For another example, in the "Sec. SC Inductance" measurement, the Inductance across the secondary winding was measured while the primary winding was shortcircuited. In an ideal transformer, if all of the flux couples from the primary coil to the secondary coil, the leakage inductance should be zero. Leakage inductance is a parasitic component of transformer design caused by poor coupling between windings [http://thedatastream.4hv.org]. The leakage inductance measurements measure the magnetic field lines that do not link the primary to the secondary.

The "Fractional Leakage" value is the fractional magnetic field lines that are not linking the 2 sides of the transformer together. The fractional leakage calculation uses the formula below for the respective primary or secondary values:

$$\text{Fractional Leakage}_{\text{pri/sec}} = \frac{\text{Short Circuit Inductance}_{\text{pri/sec}}}{\text{Open Circuit Inductance}_{\text{pri/sec}}}$$

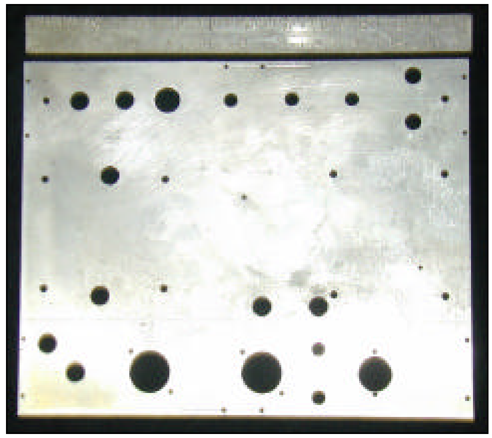
Output Transformer Comparison for Z sec. = 4 ? (Measurements made with 1 kHz sinusoidal input)		
	1968 Fender Silverface Champ	**Handwound Transformers 25 W / 5000 ?**
Primary Resistance	270 ?	142.9 ?
Output Resistance	0.3 ?	0.4 ?
Pri. OC Inductance	4.92 H	6.58 H
Pri. OC Dissipation	0.174	0.266
Sec. OC Inductance	2.14 mH	7.53 mH
Sec. OC Dissipation	0.179	0.294
Pri. SC Leakage Inductance	345 mH	15.33 mH
Pri. SC Dissipation	1.777	3.73
Sec. SC Leakage Inductance	36.4 µH	22.6 µH
Sec. SC Dissipation	1.827	4.74
Primary Load Impedance, Zpri Using Equation 1	for Z sec. = 3.2? ? 7,360? for Z sec. = 4.0? ? 9,200?	for Z sec. = 4.0? ? 3,495 ?
Primary Load Impedance, Zpri Using function gen. & Equation 2	for Z sec. = 3.2? ? 6,750? for Z sec. = 4.0? ? 8,435?	for Z sec. = 4.0? ? 3,460 ?
Pri. Fractional Leakage	**7.0 %**	**0.2 %**
Sec. Fractional Leakage	**1.7 %**	**0.3 %**

Output Transformer Comparison for Z sec. = 8 ? (Measurements made with 1kHz sinusoidal input)		
	Angela Instruments 8 ? secondary winding	**Handwound Transformers 25 W / 5000 ?**
Primary Resistance	243 ?	142.9 ?
Output Resistance	0.4 ?	0.7 ? for 8 ? winding 0.4 ? for 4 ? winding
Pri. OC Inductance	7.04 H	6.58 H
Pri. OC Dissipation	0.215	0.266
Sec. OC Inductance	10.4 mH	17.23 mH
Sec. OC Dissipation	0.251	0.303
Pri. SC Leakage Inductance	163.1 mH	15.33 mH
Pri. SC Dissipation	1.009	3.73
Sec. SC Leakage Inductance	115.9 µH	38.2 µH
Sec. SC Dissipation	1.010	4.74
Primary Load Impedance, Zpri Using Equation 1	5,415 ?	3,055 ?
Primary Load Impedance, Zpri Using function gen. & Equation 2	5,490 ?	2,733.4
Pri. Fractional Leakage	**2.3 %**	**0.2 %**
Sec. Fractional Leakage	**1.1 %**	**0.2 %**

We were pleased with the results of these transformer tests. As is shown above, the Fractional Leakage is considerably lower in the Handwound transformer than in the other two Champ-type transformers. This measurement of Fractional Leakage Inductance sonically affects the high frequencies: the larger the fractional leakage inductance, the more loss in high frequency output. These measurements would then be quantitative evidence for the reason the Handwound Transform sounds so much better than the other two transformers. However, the size and weight of the Handwound Transformers caused the first problem with the light aluminum chassis I had originally intended on using.

Construction:

In order to support such large transformers, the material of the chassis needed to be robust but at the same time still soft enough to punch holes through it for the controls and tube sockets. We decided that 6061 T6 aircraft-grade aluminum was a good choice for the chassis material, and 12 inches by 9 inches was the minimum footprint for the sheet given the large transformers. After the component placement was laid out on drafting paper, the holes for the switches, controls, and tube sockets needed to be punched. Using an upright drill press, we drilled small holes in the aluminum and used Greenlee chassis punches for the various size holes. The figure below shows the holes punched in the sheet of aluminum, with a 12-inch ruler for reference. The sheet then had to be bent to a U shape. To help strengthen the chassis, 2 aluminum sides and a center strap would be attached (see Appendix for schematics). With the rest of the of the parts ordered from Antique Electronics Supply (www.tubesandmore.com) and the fiber board from Weber VST (www.webervst.com) it was time to start constructing the circuit.



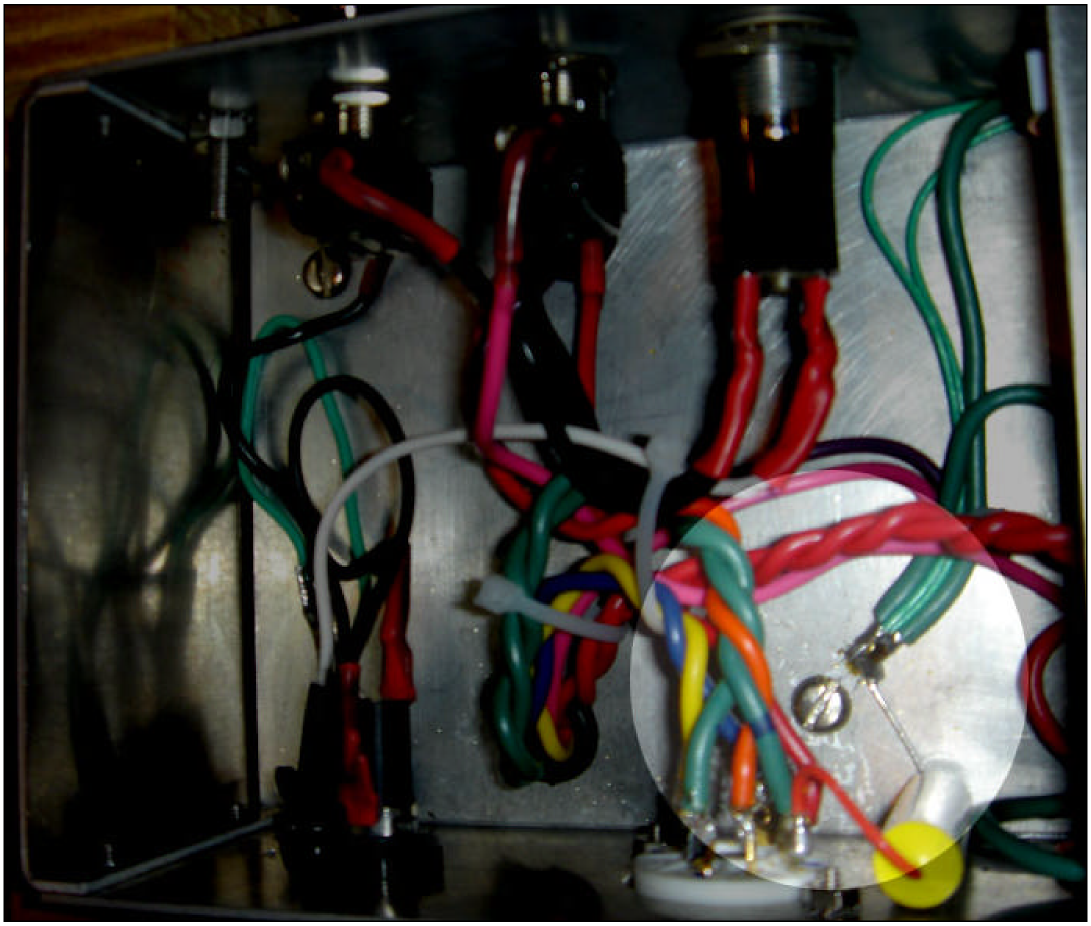
Flat Aluminum Chassis w/ Holes Punched 1

Once the transformers were fastened to the back of the chassis, the power supply stage was wired up. This includes the AC Line chord, the power switch, pilot light and tube rectifier socket. Open-circuit, no-load voltage readings were taken after this stage was wired. The primary side of the transformer had a RMS voltage across it of 122.7 $V_{AC.}$ The secondary side windings had voltages of 645V_{AC}, 7.21V_{AC}, and 6.1$V_{AC.}$

One modification I made to the original Fender schematic was the addition of a standby switch. The standby switch is used to cutoff the B+ voltage to the tubes while the heaters in the tubes are warming up. Because the B+ voltage from the transformer needs to be dissipated somewhere, we installed a 4000V 0.033 µF metallized mylar film capacitor just upstream of the standby switch. Also, if I ever decided to use a solid-state rectifier solution to take the place of a rectifier tube, I would need a standby switch in order to protect the tubes because of the solid-state rectifier's extremely quick power-up time.

A fiberboard measuring approximately 3 in. x 6 in. was purchased from Weber VST (www.weberVST.com). This fiberboard has eyelets specifically placed for the basic layout of a Fender 5F1-A Champ-style amp and was an inexpensive solution for laying out the main circuit. The fiberboard was laid out and soldered outside of the main chassis, and then placed in the chassis as one unit. It would have been extremely difficult to solder all of the connections while working inside the chassis. All of the high voltage leads on the capacitors were wrapped with heat-shrink as a safety measure. We did run into an obstacle when placing the fiberboard inside the amp chassis, however. The width of the giant transformers on the back was not wide enough for the fiberboard to fit in between the transformer mounting bolts, and thus the nuts that secured the output transformer were blocking the fiberboard's contact with the chassis. It is important (from noise reduction and amp stability) that the fiberboard be flush with the chassis and also secure, so that none of the solder joints and connections come loose as the amplifier is used and moved around. Professor Errede devised a solution to this problem in the form of aluminum spacers approximately ? " high so that the fiberboard could fit underneath the nuts. After slightly filing down the spacers, the fiberboard fit perfectly in the chassis, and we were ready to wire the circuit components to the tube sockets.

When the circuit was completely connected to the various pins on the tube sockets, we were able to concentrate on the input jacks and potentiometers. Professor Errede recommended I use Marshall-style input jacks (so as to connect input signal ground at the star ground {see discussion below}, to help reduce AC hum/noise pickup) and to use coaxial cable inside the amp, also to help shield the input guitars signal from induced AC hum and noise pickup. The cable from the guitar to the amp is coaxial, so why stop using it when the signal enters the amp? The coaxial cable used was of type RG174 and has a heavy braided wire shield surrounding the inner conducting wire. The RG174 has lower capacitance per unit length than guitar cable: 30 pF per foot as opposed to guitar cable, which has a capacitance of approximately 60 pF per foot. Coax cable was used for transporting the critical signals from the input jacks to the 1st state preamp tube, from the output of the 1st stage preamp tube to the volume and tone control pots, to the grid of the power tube and also for the presence control pot/feedback loop. Only one end of the braided shield of each coax cable was (locally) grounded, in order to avoid ground loops. Also, the 68 K "grid-stopper" resistors on the input coax cable to the 1st stage preamp tube were mounted directly on the input grid of the 1st stage preamp tube, rather than at the input jacks, again in order to reduce AC hum and noise pickup. The results of using coax cable for were very successful and there are measurements to support the low level of AC hum and noise present in the amp. Also, to further reduce induced AC hum pickup, the 6.3 V_{AC} filament wires were twisted tightly together and kept well away from the rest of the amp's circuitry. A presence control was added using a 5K linear potentiometer and a 1 μF 50 V non-polarized metallized-film capacitor. This was added to the original Princeton 5F2-A design because we wanted some variability/tonal-versatility on the amp's feedback loop. Another recommendation made by Professor Errede was to assembly the layout with a star ground. A star ground is a designated point on the chassis, with a ground lug in my case, that all of the ground signals return to. This configuration reduces ground noise and eliminates the possibility of ground loops in the circuit, which can be noisy and problematic. The star ground in my amp is in the bright circular region in the photo below.



Results & Calculations:

In my experience as engineer at the University of Illinois, I have learned that circuits do not work the first time you power them up and they inevitably need to be corrected in some way. However, because of Professor Errede's advice: taking every step slowly, double-checking your work, and never cutting corners in the assembly stage, the amplifier was fully operational on the very first try! I was very surprised and pleased.

But before we could plug a guitar into the amp, some measurements were taken to ensure that the voltages at different parts of the circuit coincided with expected values. With these measurements, we can examine further characteristics of this amp. The following measurements were taken without any input and 3 tubes from Professor Errede's personal collection: a Mesa 5U4GB rectifier tube, an RCA 6L6 "Blackplate" old-stock power tube, and a Telefunken 12AX7 old-stock pre-amp tube. The B^+ standby voltage was 449 V_{DC} and when operating, the B^+ voltage was at 392 V_{DC}. When the amp was operating with all knobs turned up full, using a 1 kHz sine wave for an input, the B^+ voltage was 377 V_{DC}, but this voltage would sag even further for input signals with a lower frequency, such as that from a guitar (low-open E ~ 82 Hz, high-open E ~ 330 Hz).

For analysis, I have calculated certain current and power levels based on these measurements. The DC current flowing through the 470 ? , 2 Watt 6L6 cathode resistor can be calculated by the following equations:

$$I_{DC\_470} = I_{DC\_6L6\_Plate} + I_{DC\_6L6\_Screen}$$

$$I_{DC\_6L6\_Plate} = \frac{V_{B+} - V_{DC\_6L6\_Plate}}{R_{primary\_output\_trans}} = \frac{392\text{V} - 384\,\text{V}}{142.9\text{O}} = 56\,\text{mA}$$

$$I_{DC\_6L6\_Screen} = I_{10K\_\text{Re}sistor} - I_{22K\_\text{Re}sistor} = 3.5 - 1.2 = 2.3\,\text{mA}$$

$$I_{DC\_470} = 56 + 2.3 = 58.3\,\text{mA}$$

It is interesting to note that the Handwound Transformer used is able to supply up to 200 mA (DC), and the 58.3 mA (DC) does not put any stress on the transformer. The DC power dissipation through the same 470 ? 6L6 cathode resistor can be calculated as follows.

$$P_{DC\_470} = V_{DC\_6L6\_Cathode} \times I_{DC\_470}$$

$$P_{DC\_470} = 26.7 \times .0583 = 1.5\,\text{Watts}$$

There was a concern that the 2 watt 470 ? resistor might not be able to dissipate the DC power associated with the cathode-biasing of the power tube, however the above calculation of 1.5 watts show that a 2 watt resistor won't cause any problems overheating. The DC power dissipation in the 6L6 plate is another interesting measurement to discuss. The calculations are:

$$P_{DC\_6L6\_Plate} = \left(V_{DC\_6L6\_Plate} - V_{DC\_6L6\_Cathode}\right) \times I_{DC\_6L6\_Plate}$$
$$P_{DC\_6L6\_Plate} = \left(384\text{ V} - 26.7\text{ V}\right) \times .056 = 20.0\text{ Watts}$$

According to the tube data sheets for this RCA "Blackplate" tube (which can be found at http://tdsl.duncanamps.com/index.php) the maximum plate power dissipation is 30 watts, so we are well within this range.

The maximum AC RMS power output is another interesting characteristic to note. We can calculate this by taking the voltage measured on the speaker squared, divided by the impedance of the load. The measurements taken were with using a 1kHz sine wave as an input and a 8.3 ? resistor load on the amp's output, with volume, tone, and presence controls all at maximum values.

$$P_{AC\_RMS} = \frac{\left(V_{RMS\_Spea\,\mathrm{ker}}\right)^2}{\text{Speaker Impedance}} = \frac{\left(9.14V_{RMS}\right)^2}{8.3\Omega} = 10.07\text{ Watts}$$

Since it would not have been safe for us to explicitly measure the voltage on the plate of the 6L6 tube while operating (e.g. oscilloscopes and oscilloscope probes are typically rated only for 400 V (absolute) measurements), we can calculate the corresponding AC voltage on the 6L6 plate by using our previous measurements of the inductances in the output transformer.

$$\frac{V_2}{V_1} = \frac{N_1}{N_2} = \sqrt{\frac{L_2}{L_1}}$$

$$\frac{9.14V_{RMS}}{V_1} = \sqrt{\frac{17.23mH}{5.58H}}$$

$$V_1 = 178.6V_{RMS}$$

It would also be interesting to note the AC voltage gains across each stage. The 12AX7 preamp tube consists of two triodes, and there are different gains through the first and second triode. The signal is also inverted in polarity as it passes through each triode stage. The three triodes (two in the preamp, one in the power tube) and the output transformer (which also inverts the signal) make an even number of inversions so the original signal is in phase. Also, the 47 K? feedback resistor is part of a negative feedback loop, where the signal at the speaker is fed back to the cathode of the second stage of the preamp. This negative feedback increases the signal bandwidth, but causes a reduction in voltage gain because the signal feeds back to the cathode of the second stage. The table shown below summarizes the voltage gains across each stage by dividing the output voltage by the input voltage for each stage of amplification in the amp.

Stage	**Input Voltage**	**Output Voltage**	**Voltage Gain**
1st Preamp Stage	0.0074 $V_{AC\ RMS}$	0.450 $V_{AC\ RMS}$	61x
2nd Preamp Stage	0.450 $V_{AC\ RMS}$	22.8 $V_{AC\ RMS}$	51x
Power Tube	22.8 $V_{AC\ RMS}$	178.6 $V_{AC\ RMS}$	7.8x
Overall Gain	0.0074 $V_{AC\ RMS}$	178.6 $V_{AC\ RMS}$	24,135x

In an attempt to measure the amount of AC hum interfering with the signal, we measured the AC rms output voltage at the speaker terminals with all the knobs turned up and no input signal. That voltage was 32.1 $mV_{AC\ RMS}$ with no input. Under the same conditions, with an input at 1 kHz and input amplitude of 7.4 $mV_{AC\ RMS}$, the output voltage on the speaker terminals was measured to be 9.14 $V_{AC\ RMS}$. We can use the Signal to Noise ratio formula to quantify the degree at which the AC hum is interfering

$$SNR = 20 \times \log_{10}\left(\frac{V_{signal}}{V_{AC\_Hum}}\right)$$

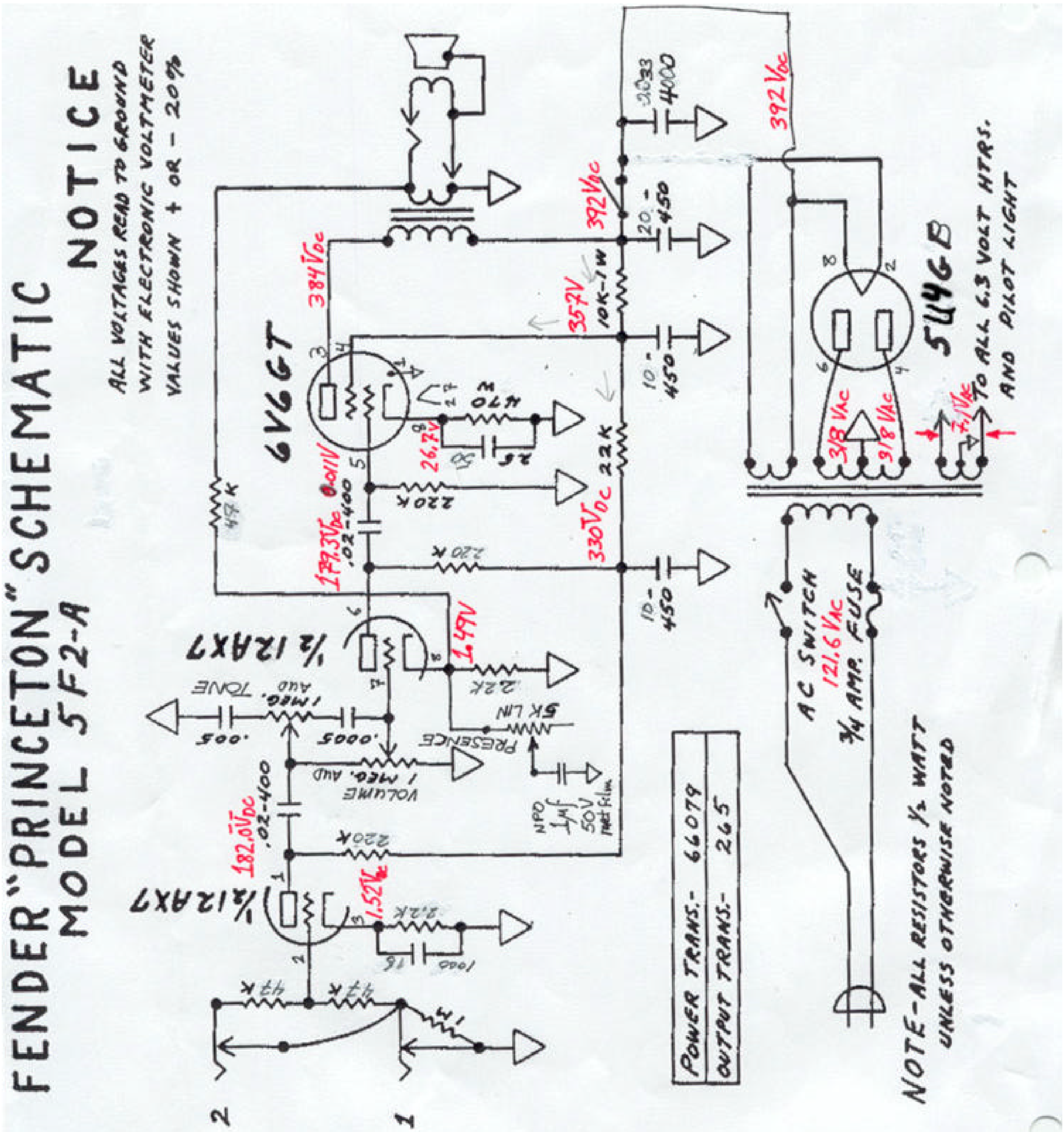
$$SNR = 20 \times \log_{10}\left(\frac{9.14\ \text{Vrms}}{0.0321\ \text{Vrms}}\right) = 49\text{dB}$$

The results of this calculation show that the AC hum is -49 dB lower than the signal. It would also be better to call this measurement the signal to hum ratio, instead of signal to noise, because it is the AC hum relative to the signal that we are measuring.

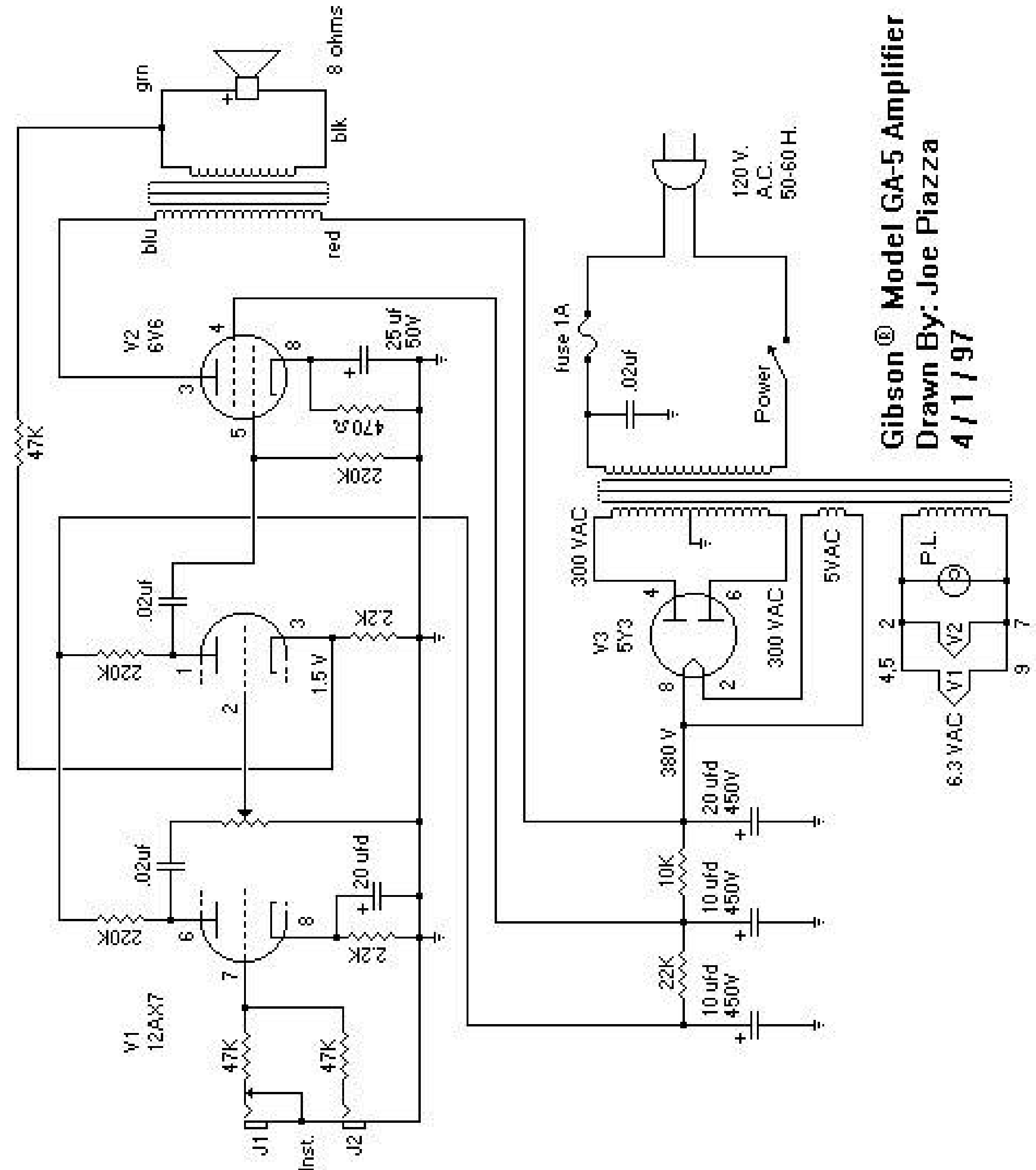
In conclusion, I believe the amp sounds fantastic! There is virtually no hum and it is much louder than I had ever thought it would be. It is perfect for a practice amp or for use as a recording amp in a studio. The quality of the tone is more pure than I thought it was going to be, yet is very warm and breaks up beautifully at higher volumes. I think it would best function as a head, so that I can swap different combinations of speaker cabinets for different purposes and sounds. I plan on building a head cabinet made out of hardwood to protect the amp, and a matching speaker cabinet with perhaps a Celestion Vintage 30 speaker in it.

Many thanks to Professor Steve Errede and

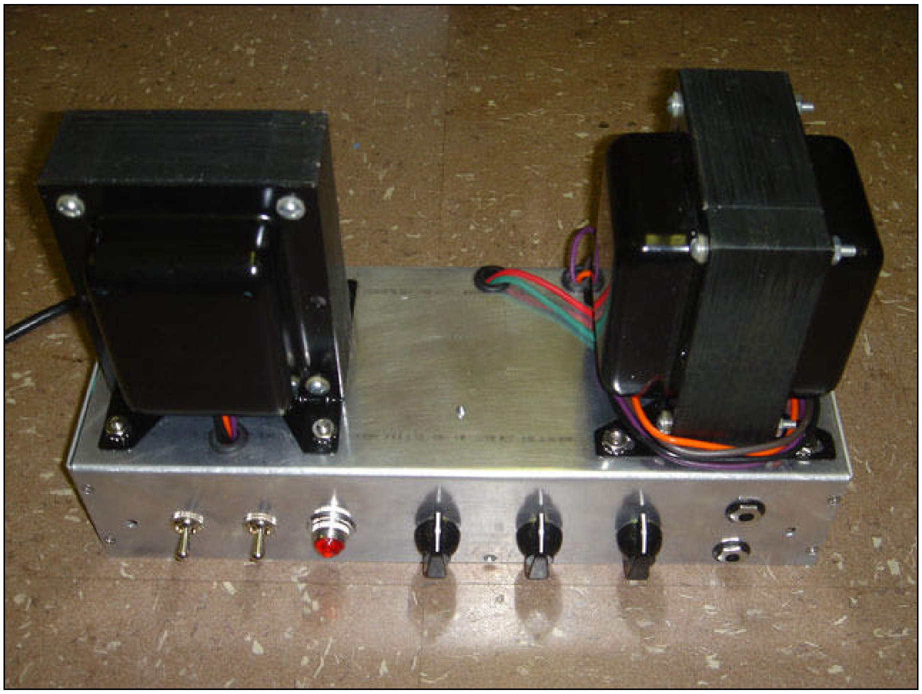
Ben Juday for all of their assistance and time!



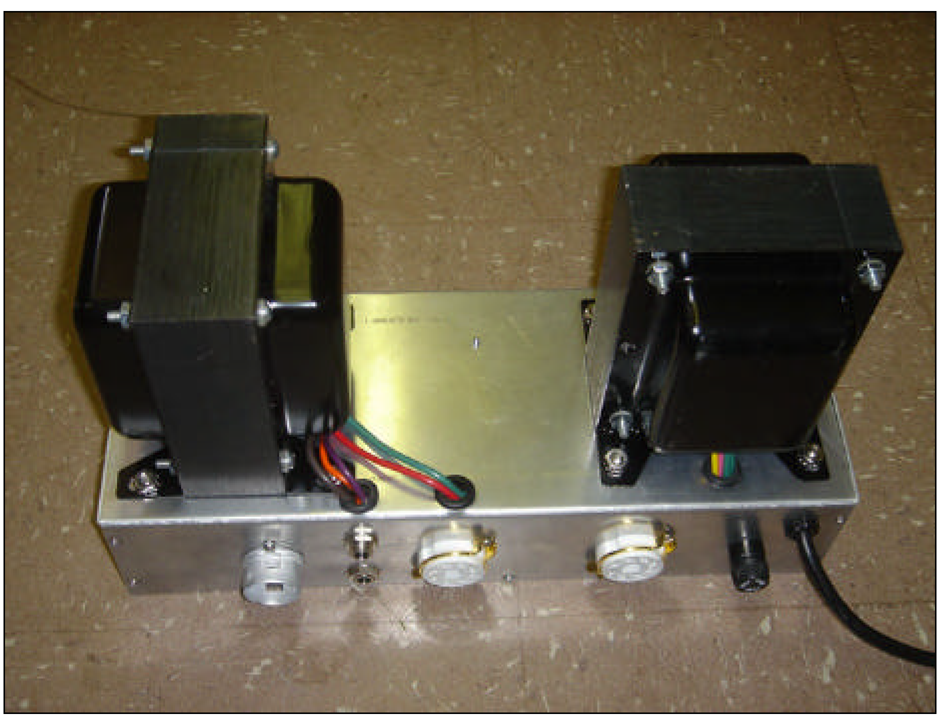
FENDER "PRINCETON" SCHEMATIC
MODEL 5F2-A
NOTICE
ALL VOLTAGES READ TO GROUND WITH ELECTRONIC VOLTMETER
VALUES SHOWN + OR - 20%
2
1
47K
47K
1 M
½ 12AX7
½ 12AX7
6V6GT
5U4GB
182.0VDC
.02-400
220K
1.52VDC
2.2K
25
1000
VOLUME 1 MEG. AUD
.0005
1 MEG. AUD TONE
.005
PRESENCE 5K LIN
NPO 1Mf 50V
1.49V
2.2K
177.3VDC
0.011V
.02-400
220K
220K
26.7V
470
25
384VDC
357V
10K-1W
22K
330VDC
392VDC
392VDC
20-450
10-450
10-450
4000
318 VAC
318 VAC
7.1VAC
TO ALL 6.3 VOLT HTRS. AND PILOT LIGHT
AC SWITCH
121.6 VAC
3/4 AMP. FUSE
POWER TRANS.- 66079
OUTPUT TRANS.- 265
NOTE-ALL RESISTORS ½ WATT UNLESS OTHERWISE NOTED



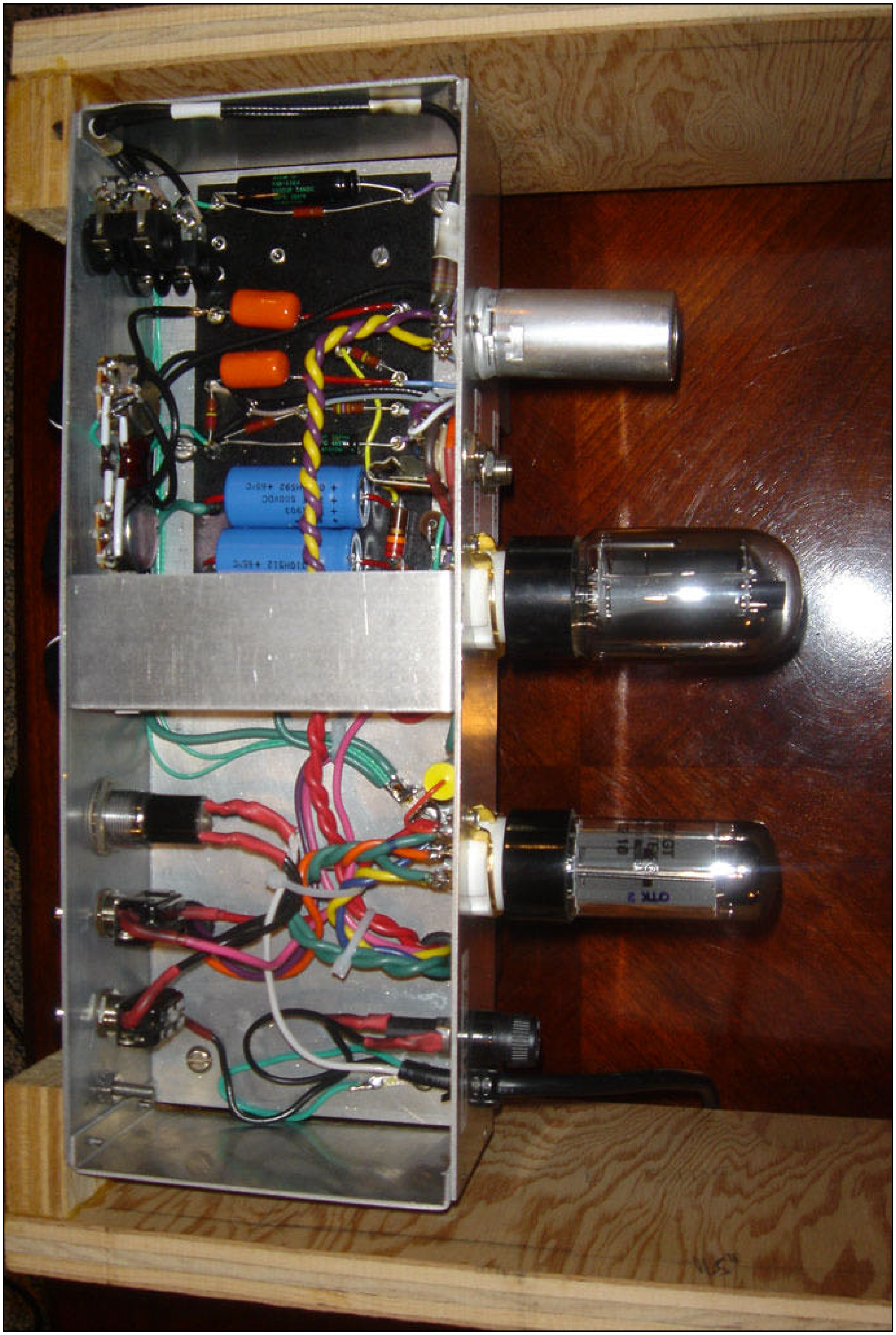
Gibson® Model GA-5 Amplifier
Drawn By: Joe Piazza
4 / 1 / 97
V1
12AX7
V2
6V6
V3
5Y3
grn
blk
8 ohms
blu
red
47K
220K
470Ω
25 uf
50V
.02uf
2.2K
1.5 V
20 ufd
22K
10K
10 ufd
450V
20 ufd
450V
380 V
300 VAC
5VAC
6.3 VAC
P.L.
fuse 1A
.02uf
Power
120 V.
A.C.
50-60 H.
J1
Inst.
J2



My Finished Chassis -Front 1



My Finished Chassis -Back 2



My Finished Amp 1