Build This MoFo!

By Mike Rothacher

Inception

I couldn't sleep. I had designer's block. It was somewhere around 2:00AM and I found myself digging through a pile of old capacitors at Electro-Bowl, an all-night electronics surplus and bowling alley. There aren't a lot of establishments where you can pick up a few transistors, then roll a few frames 24-7. I'd been there on more than a few sleepless nights. It kept me off the streets.

I could hear the rain outside tapping on the metal roof of the fourteen-thousand square-foot Quonset hut that was home to fifty-odd years of curated electronic detritus and ten well-worn but always freshly-waxed lanes. The proprietor, Carl, sat behind the counter listening to his favorite late night AM radio station. The radio host was jabbering on about alien bases on the moon, or something like that.

Carl looked at me over his reading glasses and cleared his throat. "Ahem, are you workin' on another DIY article, kid?" Carl asked. I had been coming to Electro-Bowl for a really long time and Carl still called me 'kid' even though I'm fifty.

"I'm trying to think of a cool project for Burning Amp," I said.

"Burning Amp? What the Hell's that?" he asked.

"It's like a comic book convention for audio nerds," I explained. "It's in San Francisco."

He shook his head. "What'll they think of next? In my day, all we had was hamfests."

"I'm trying to come up with a fun amp project I can take to the show."

Carl pondered this for a moment. “You should talk to The Dude about your project. I bet he can help. He’s here tonight.”

“The Dude’s here now?” I croaked. The Dude was legendary. Some say he’d been some kind of rocket scientist or particle physicist who left the science racket to pursue a monastic life of meditation and designing audio gear. He was widely known as an audio guru of the highest order, and one hell of a good bowler.

“He’s on lane 7,” Carl said, glancing toward the far end of the store. He held out a pair of size elevens for me. “Shoe rental is on the house tonight. Good luck, kid.”

I laced up my bowling shoes, turned, and walked slowly past the parts aisles, Transformers, Tubes, Semiconductors, then past lanes 1 through 6. A short distance away stood The Dude waiting for the pins to reset. The Dude was wearing a grey bathrobe over a black pocket t-shirt and SpongeBob pajama bottoms with bowling shoes. He had a beard, long, slightly unkempt hair, and he wore dark sunglasses despite the time of day.

“Always check the date codes,” he said taking notice of me, but not looking up.

“Excuse me?” I said.

He pointed to the box of power supply caps I had under my arm. “Carl never gets rid of anything, and he’s had some of those caps since the 70’s, so you gotta check the codes.”

“Oh, right Dude,” I said. “good advice.”

He grinned. “So, what’s up, man? I heard you need some help with your project for Burning Man.”

“Well, it’s Burning *Amp* actually, but yes, I’m kinda stuck.”

“Yep. You got designer’s block alright. That’s cool, man. I can help out.”

“Awesome, thanks, Dude.” I said.

“Ok, so what do you have in mind?” he asked as he shuffled silently up to the foul line and rolled.

“Well, I’d like to do something really simple that beginners will like.”

“Okay,” he said, without looking back, as all ten pins went down with a splash. Strike!

“Um, really low parts count, and easy to solder-up and listen to in a few hours,” I said.

“Alright.”

“Class A, of course. I’m thinking single-stage, single-ended, with high input impedance, and a nice low output impedance to drive my latest speaker project,” I continued.

“Uh-huh,” He said, waiting beside the ball return.

“Low distortion, good bandwidth, not too expensive, and buildable with easy-to-find parts, nothing exotic.”

The Dude grinned. “Wow, man, that’s a pretty long list. I guess you want it to sound good too.”

“Well, you asked, Dude,” I said, looking down at my shoes.

The Dude thought for a minute, snapped his fingers, then, nodding he said, “No problem, man. You should make a MoFo!”

“I’m sorry, make a what?”

“A MoFo. You know, a MOSFET Follower.”

“Oh, right Dude. I get it.”

“There’s no voltage gain and you need a preamp that can swing all the voltage for your full output power, but it checks all the boxes, man.

You get low-distortion, high input impedance, low output impedance, and good bandwidth since there's no Miller effect. It's single-stage, single-ended, and really, really simple." He tore-off a blank scoresheet, turned it over, sketched something on the back and handed it to me. "Here you go, man! It doesn't get much simpler than that."

Here's the schematic he gave me:

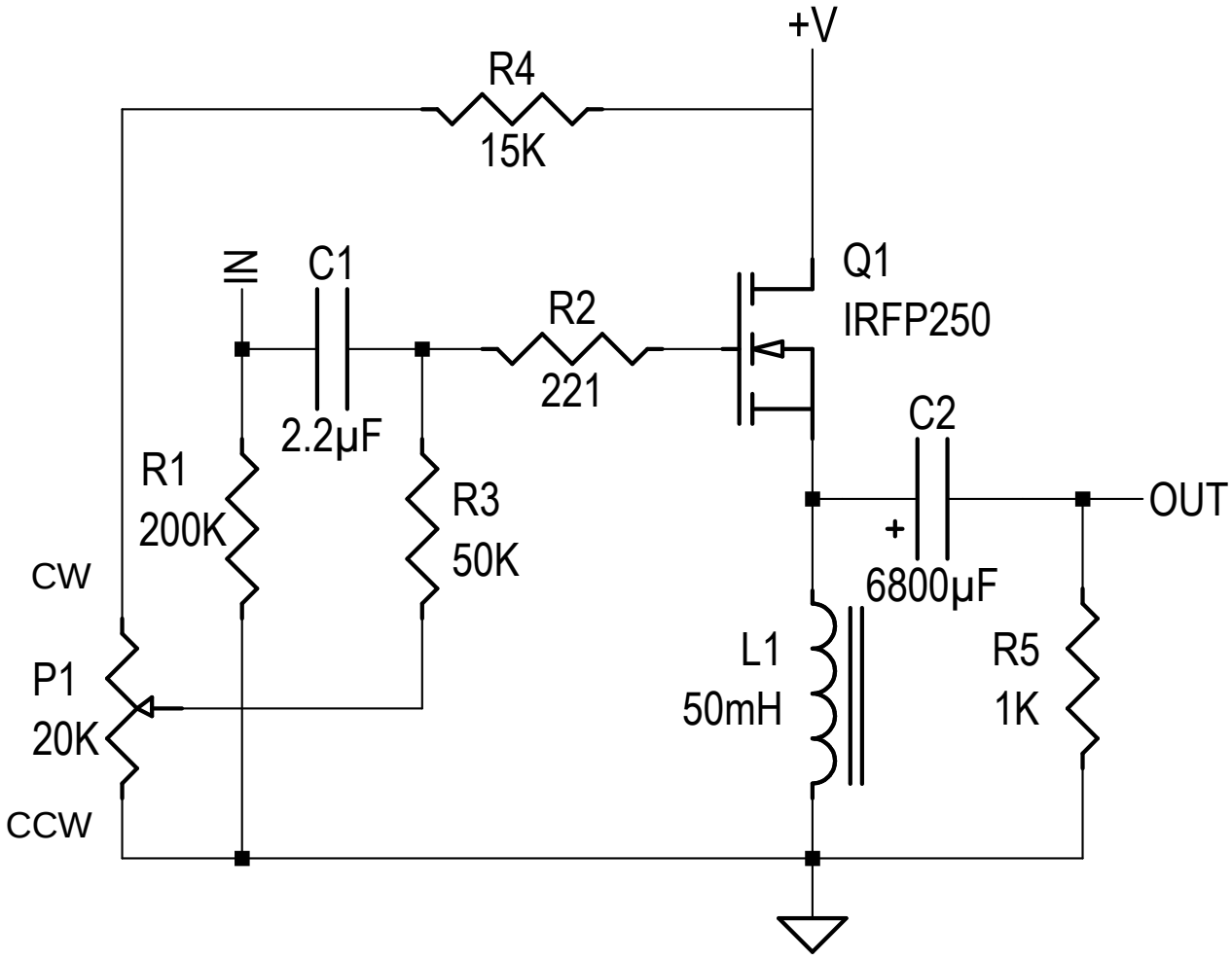

Figure 1

"Wow, that *is* simple," I said, "but what about the power supply?"

"Just use one of those laptop switchers," he said "that'll be great for beginners. You could use anything decent from like 12 to 24 volts."

"Oh, great, but don't those have a lot of ripple, Dude?" I asked.

“Sure, but the really high Drain resistance of the IRFP250, and the fairly low resistance of the inductor at the ripple frequency divide down the ripple voltage, so you won’t get a lot of noise on the output,” he said as he lined up for another roll.

I waited for him to finish. Rumble. Crash. Strike! I studied the schematic and fixated on L1, the inductor attached to the MOSFET’s Source. “Dude, won’t the Source degeneration raise the output impedance?”

He pointed to the schematic. “Chill, buddy. This is a Source Follower. You’re taking the output from the Source, not the Drain, and the feedback is voltage-derived series-mixed, so you get effective curves that are more ‘triodey’ than a triode.”

I wasn’t entirely sure what The Dude meant by ‘triodey effective curves’ but I decided to let that sink into my subconscious for a while. “So, why use an inductor anyway? Why not a current source or something?”

“Wow, man, I can see you like to worry about stuff,” he said.

“Sorry, Dude. I guess it’s an audiophile thing.”

He took a seat on the bench across from me and adjusted his sunglasses. “Well, for convenience and safety, we’re using laptop power supplies, and they work really great here, but you’re limited to the lower voltages they offer, like 12 to 24 volts. So, if you want to get some real power out of this amp, you need a little a little trick to boost the efficiency. The inductor handles this without any special active circuitry because it can store energy in its magnetic field. The energy gets stored and released under the control of the gain device, and as a result, the amplifier can deliver almost twice the supply voltage to the load and the efficiency approaches 50%. Plus, we’re able to use a smaller inductor in this circuit because the load’s in parallel with the really low Source resistance of the MOSFET.” Then he lowered his shades a little and looked me in the eye. “And, it’s simpler.”

“Oh, I get it. That’s clever, Dude. So, will it sound good?”

“Well, you gotta build it and judge for yourself my friend, but I think you’ll be dig it.” The Dude stood up. “Well, it looks like my bowling partners are here. Say hello to Al and Dick.” Two guys walked up, their names were stitched on their bowling shirts, Einstein and Feynman.

I shook my head a few times in disbelief, then my vision went blurry. Just then, music began playing on the loudspeakers overhead. It was indistinguishable. There was singing, was it French? Then, over the music, loud steady beeping. “Dude, what’s that beeping?” I asked.

The Dude grinned back at me. “Time to wake up, man. Now go build something.”

“Huh?”

My alarm clock wailed.

I turned off the alarm and rubbed my eyes, took out some graph paper and sketched the schematic from my weird dream. It *was* a dream, right?

MoFo Mojo

Figure 2 shows how the feedback works in the Source Follower.

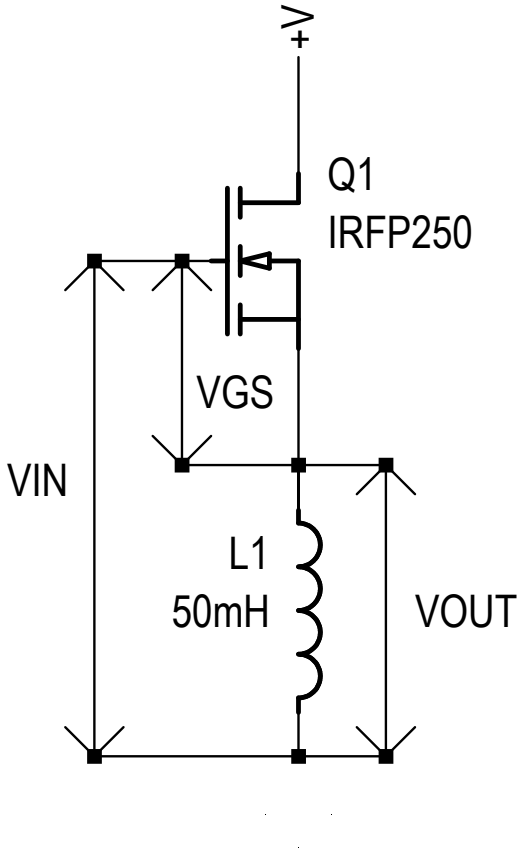

Figure 2

The inductor loads the Source and the output signal appears across the inductor. The Gate-Source signal is the difference between the input and output signals (VIN – VOUT = VGS).

Figure 3 shows a set of characteristic curves for an IRFP250 MOSFET. They sure look a lot like Pentode curves, so what was The Dude talking about when he said MoFo has ‘triodey’ curves?

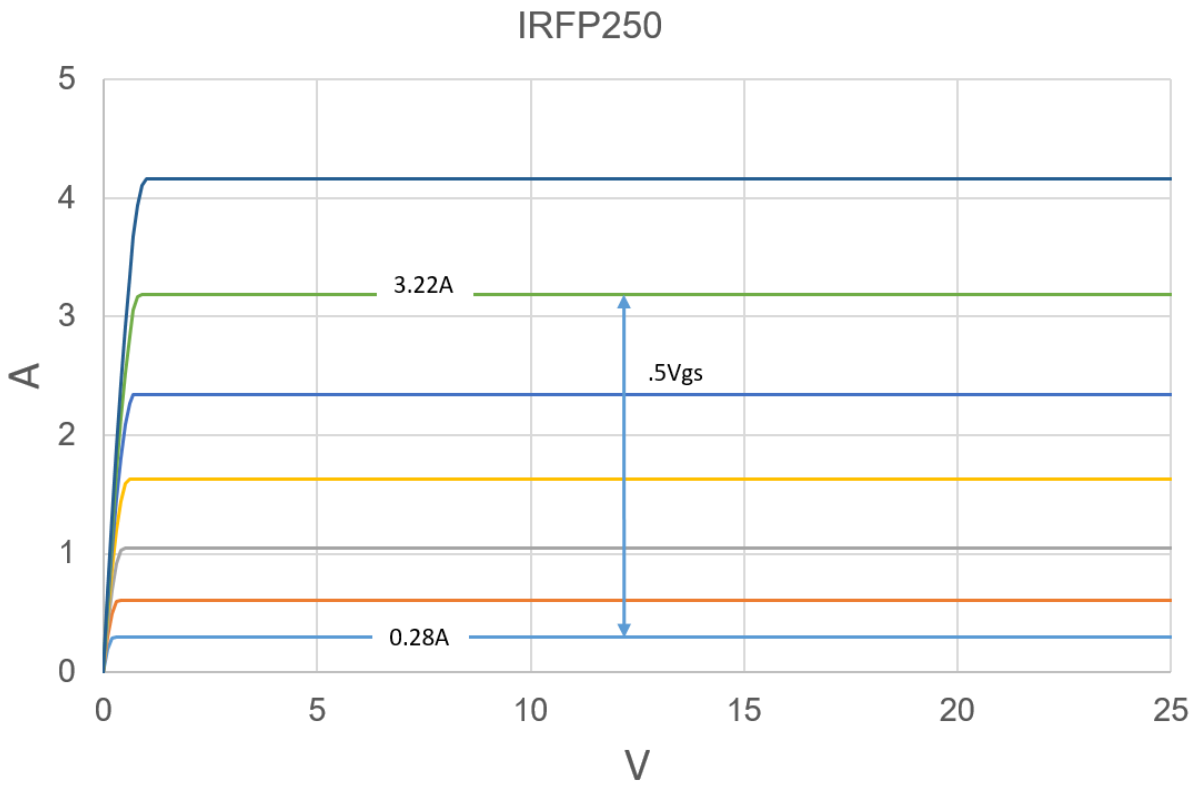

Figure 3

Well, the source follower can be thought of as a special case of voltage negative feedback where 100% of the voltage derived at the output is mixed back in series with the input. Like other forms of voltage negative feedback, it has a 'triodey' effect on the characteristics of the gain device, making the IV curves more vertical. It will lower the gain, distortion, and output impedance.

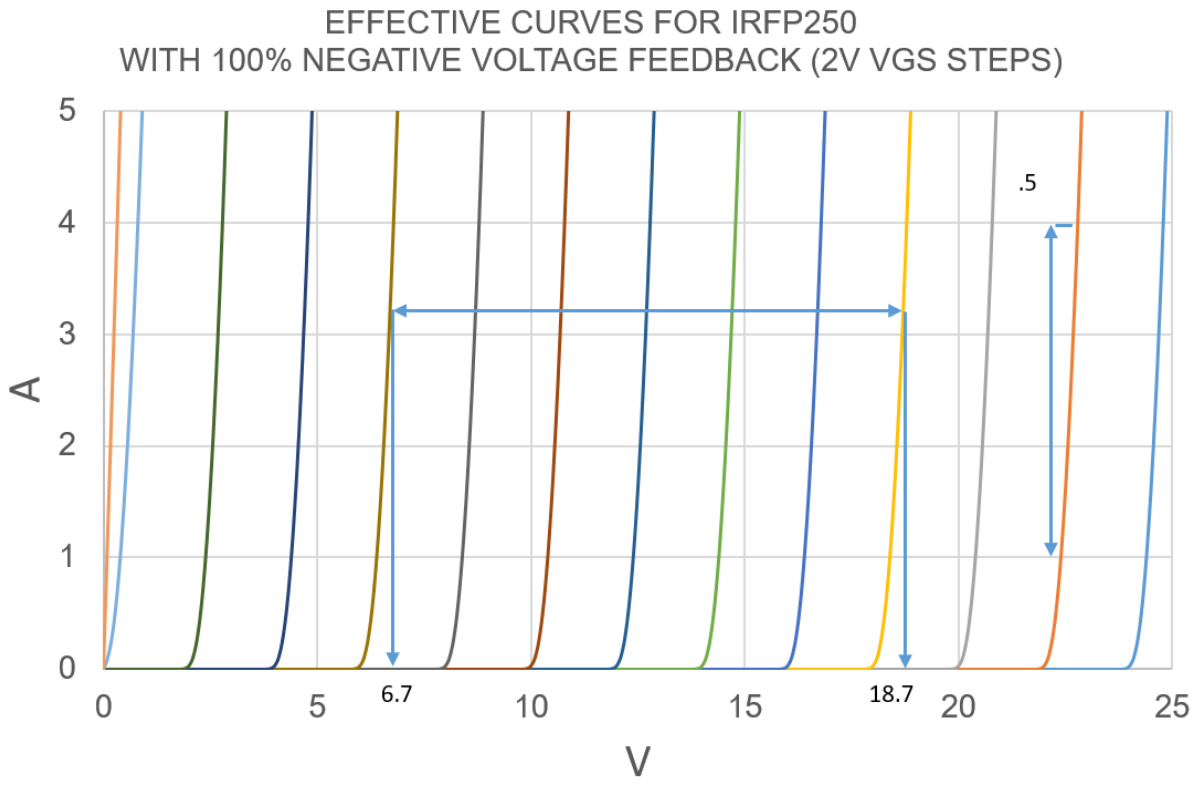

Figure 4

Figure 4 shows the effective characteristics for an IRFP250 with 100% series negative feedback applied. Without any math at all we can see that we have low output resistance (vertical curves), low distortion (evenly spaced parallel curves), and little or no gain.

Since this indeed looks sort of 'triodey' let's analyze Figure 4 in triode terms in order to understand the interrelationship between these two sets of IRFP250 curves. The output resistance for Figure 4 is the slope of the curve, which is the change in voltage divided by the change in current or:

$$rS = \frac{\Delta V}{\Delta I} = \frac{.5}{3} = .17\ Ohms$$

The amplification factor is the change in Drain voltage divided by the change in Gate voltage:

$$\mu = \frac{\Delta Vd}{\Delta Vg} = \frac{12}{12} = 1$$

Ok, so next let's talk about transconductance, which in triode terms is mu over the output resistance:

$$g_m = \frac{\mu}{rS} = \frac{1}{.17} = 5.88s$$

And now we turn back to the curves without feedback applied. We don't normally think of MOSFETs as having mu, so we calculate the transconductance of Figure 3 as the change in output current over the change in input voltage:

$$g_m = \frac{\Delta I}{\Delta V} = \frac{2.94}{.5} = 5.88s$$

We notice that transconductance is unchanged between the two sets of curves. Transconductance is the same, but we've lowered the output resistance and the gain.

Now, we normally calculate the output impedance of a MOSFET Source Follower as the inverse of the transconductance:

$$rS = \frac{1}{g_m} = \frac{1}{5.88} = .17\ ohms$$

And (Tada!) we see that's the same output resistance we get from our 'triodey' effective curves.

So there we go, we have a different way of looking at what feedback really does and how it changes the gain device characteristics. Neat huh?

So, is The Dude saying this will sound just like a triode? No, not exactly. He probably wasn't being quite so literal, but it's likely to compare more closely to a Cathode Follower than a Common Cathode compares to a Common Drain. If I ever finish my Cathode Follower with 16 6AS7's, I'll let you know. Like The Dude said, you have to try it for yourself.

MoFo Measurements

MoFo's input impedance is around 50K ohms, and the output impedance is around .2 ohms, for a damping factor of 40.

Noise (22Hz-22kHz) was around 3uV with the switching power supply I used. Yes, 3uV.

Figure 5 shows the THD vs. Output Power in watts. This is with a 19V power supply, biased at 1.7A, and you can see we're making around twelve watts. The Hammond 193T inductor will handle 2A and you could consider taking the bias up a little for a little more power and a little less distortion, providing your PSU and heatsink are okay with that. I left a little margin. The 12V and 15V curves (also at 1.7A bias) are identical except, of course they clip earlier due to the lower rail.

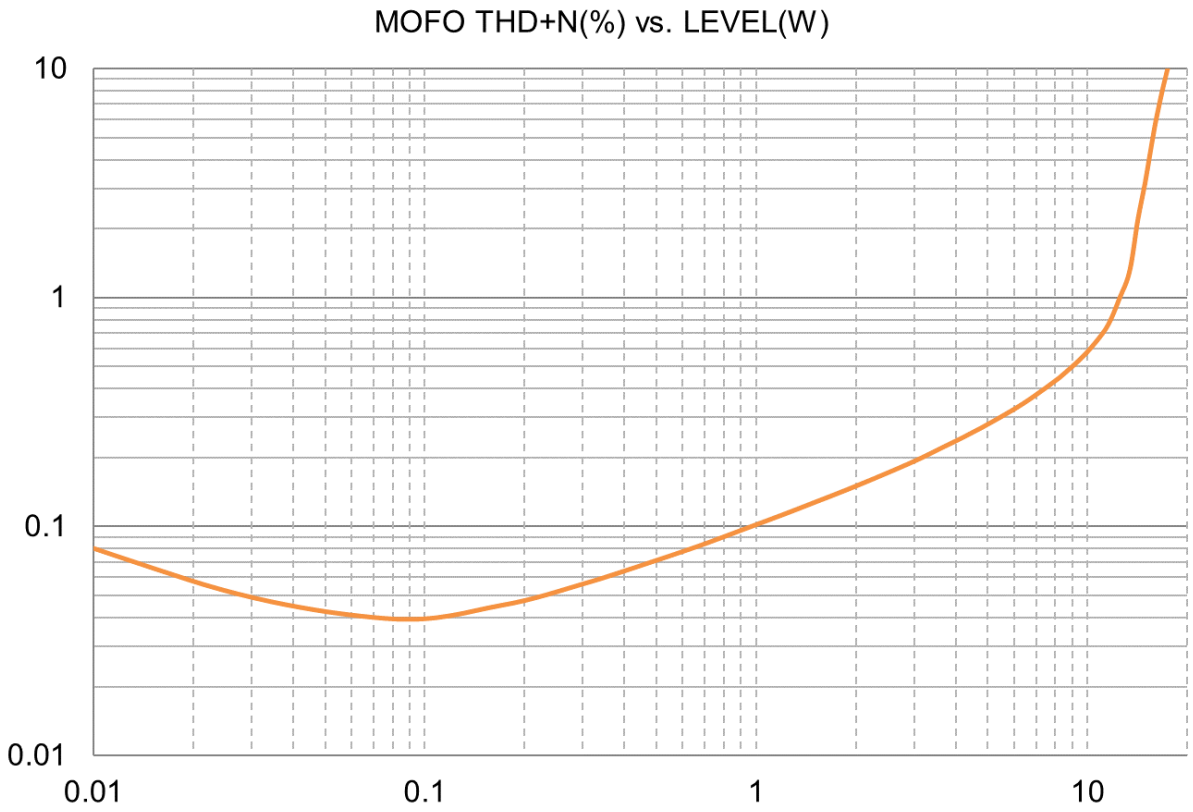

Figure 5

Figure 6 shows the frequency response, a little less than 2dB down at 200kHz.

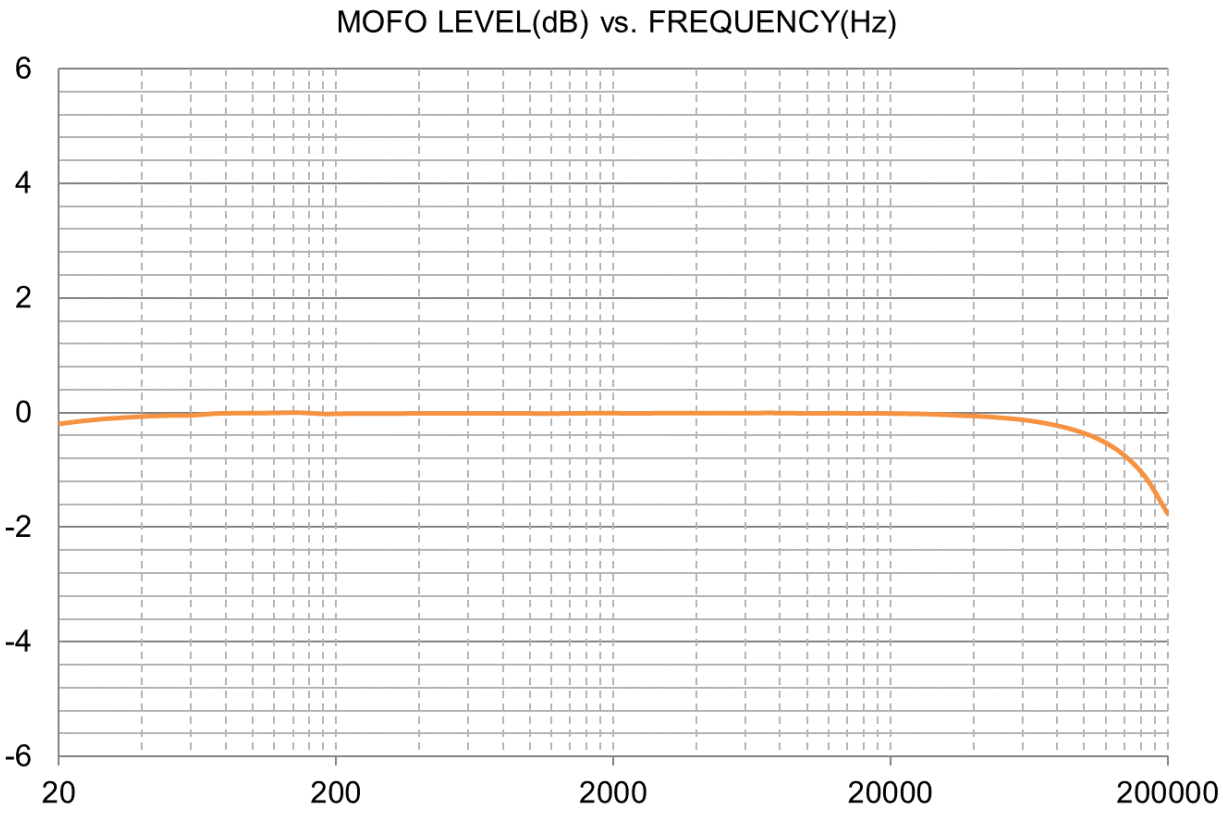

Figure 6

Figure 7 is the THD vs. Frequency. Note the reduced (not rising) distortion at high frequency.

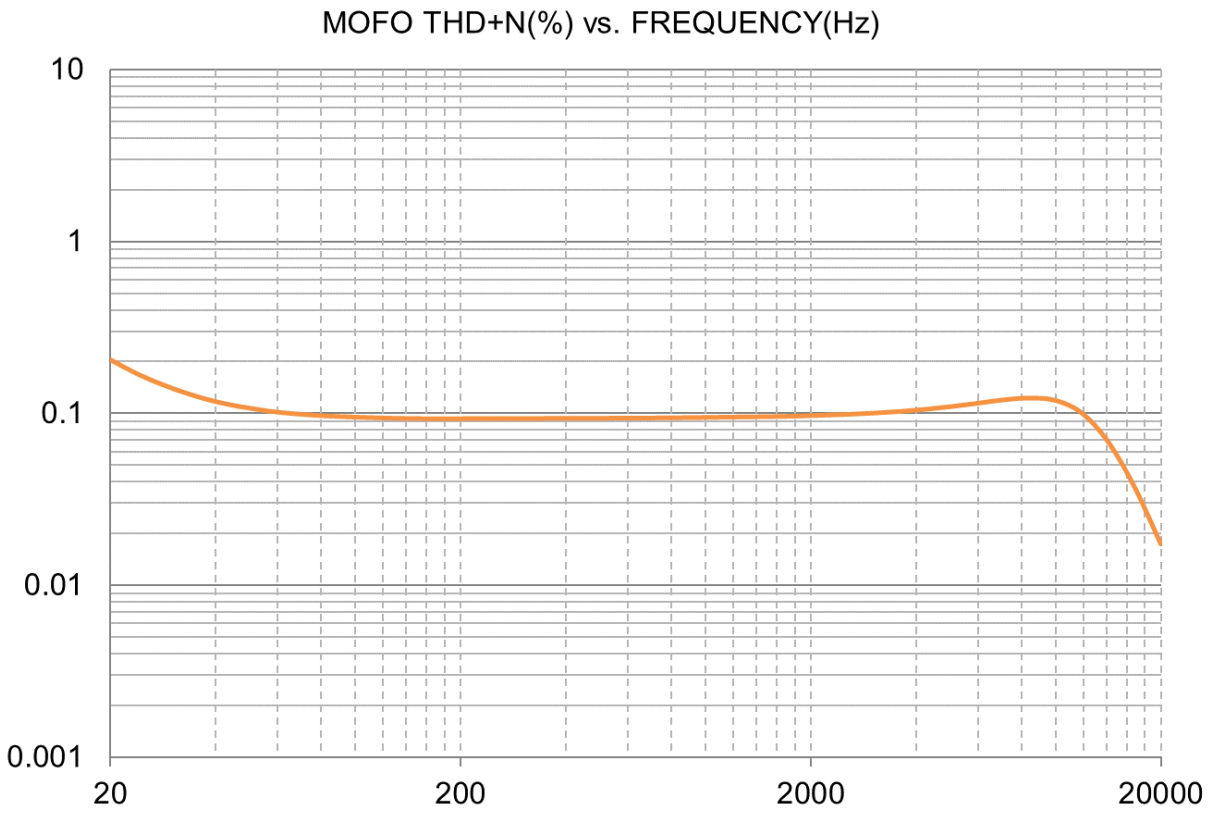

Figure 7

Figure 8 is the THD vs Output Power in watts for Big MoFo, the 24V version biased at 2.5A. You can see the higher bias nearly halves the distortion, and we're making it to 22 watts or so. If this tempts you to build the big one, you'll need a bigger heatsink and the much larger Hammond 193V inductor.

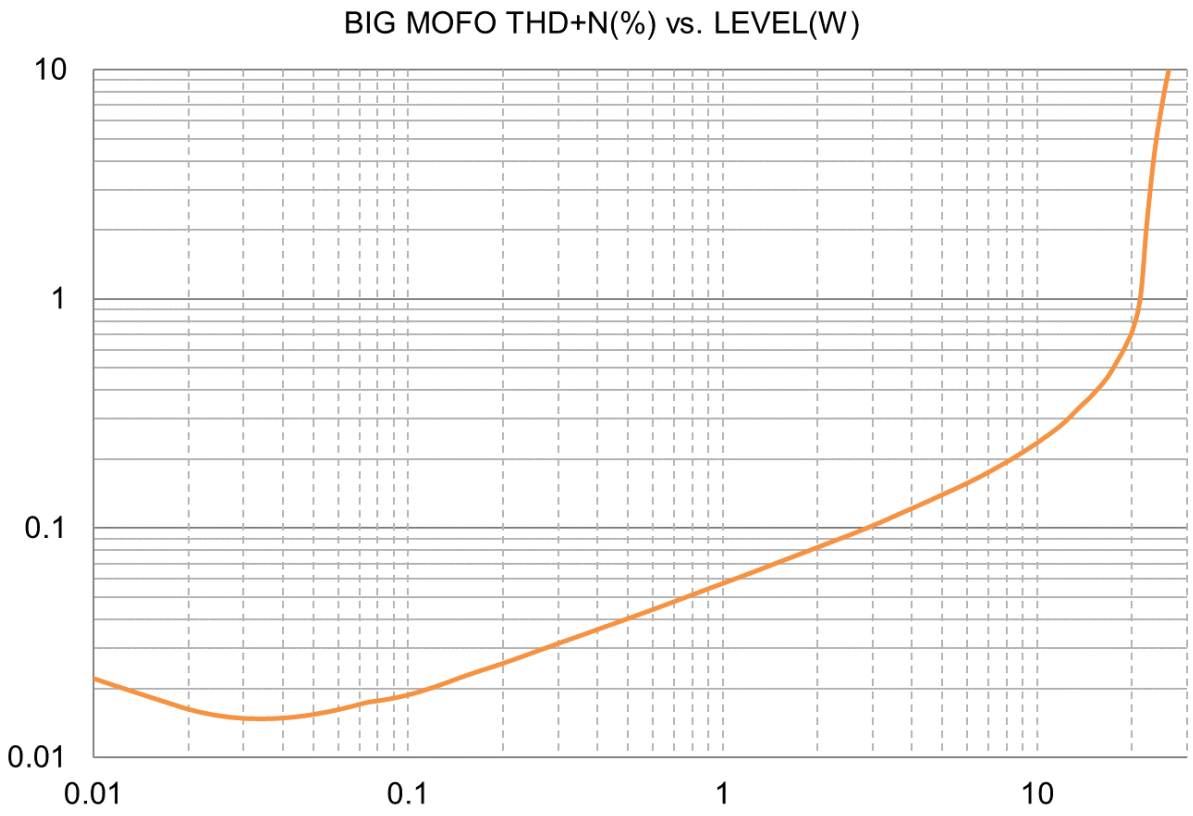

Figure 8

Here's Figure 9, a picture of a 10kHz squarewave, because who doesn't like pretty pictures of squarewaves. And, finally, figure 10 is the THD spectrum at one watt. You can see the second harmonic at about -60dB and the audiophile-approved declining staircase of third, fourth, fifth, and sixth, vanishing into the noise floor.

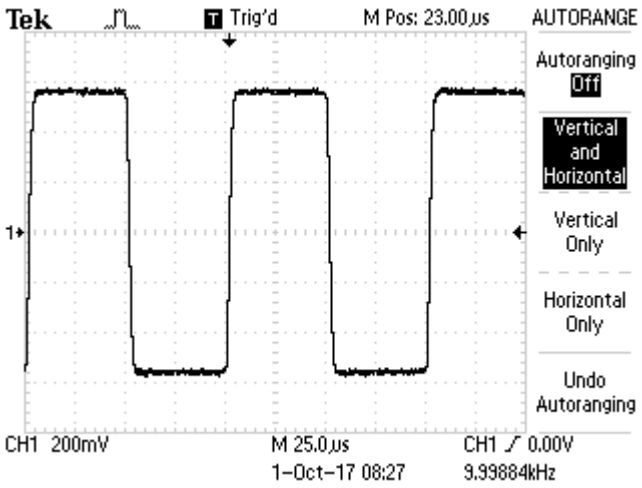

Figure 9

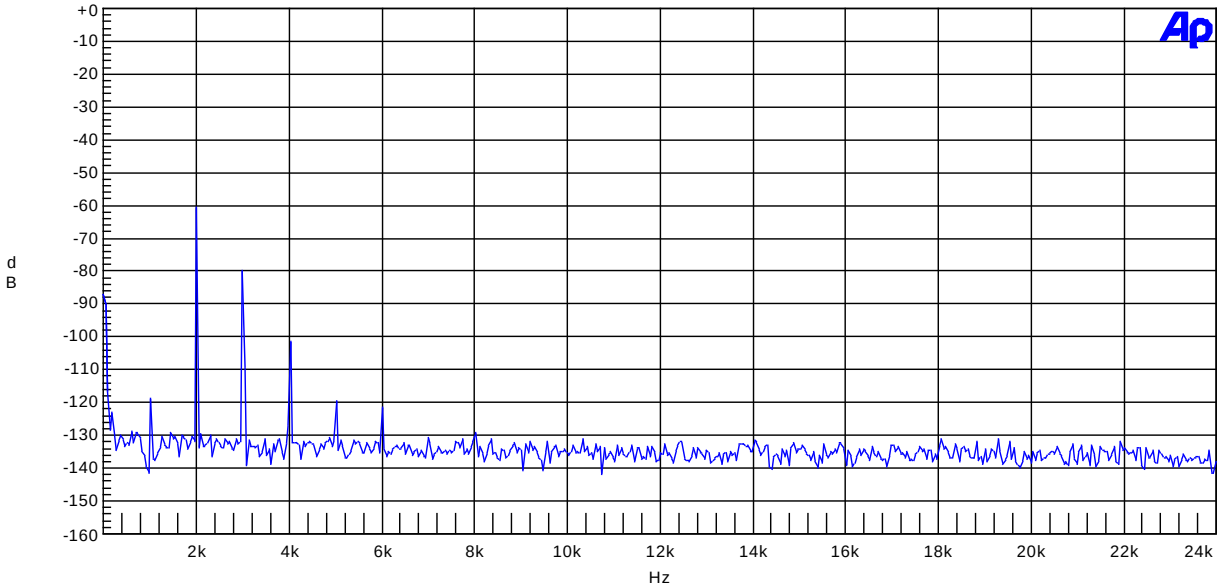

Figure 10

Building MoFo

Table 1 is the parts list. The parts will set you back around fifty bucks per channel without the power supply and heatsink. These project articles usually draw a lot of questions about part substitutions and so on. Rest assured, I tried lots of different parts, and those on the list are what I recommend if you want your experience to be consistent with mine. On the other hand, I understand some of these parts might not be readily available in your area, or you really like to experiment, in which case I'll share a few thoughts on alternative parts here.

Part ID	Value	Part#	Qty. Per Channel
R1	200K 1/4W		1
R2	221 1/4W		1
R3	50K 1/4W		1
R4	15K 1/4W		1
R5	1K 1/4W		1
P1	20K Trimmer	Mouser 652-3296W-1-203LF	1
C1	2.2uF or greater film cap	Parts Express Part # 027-110	1
C2	6800 uF 25V	Mouser 647-UFW1E682MHD	1
Q1	IRFP250	Mouser 942-IRFP250NPBF	1
L1	50mH Hammond 193T	Mouser 546-193T	1
Z1 (Optional)	20V Zener	Mouser 512-BZX79C20	1
Power Supply	19V Switching	Mouser 709-GST90A19-P1M	1

Table 1

You could substitute other MOSFETs, the old favorite IRFP240 for example, but the IRFP250 is just about optimal here, and they're dirt cheap. I know some of you might want to experiment with Q1. I tried lots of other parts. I tried fancy, expensive parts from Cree and they did not have lower distortion. I also tried obsolete parts from Semisouth and Fairchild and they had *slightly* better distortion performance, but they're unobtanium and of dubious merit here anyway.

If you try other MOSFETs and experience oscillation, you can increase the value of R2 until it stops. I found this to be the case with several of the low-capacitance Cree parts and took R2 up to 470 ohms or more. If you're trying to adjust the bias and things go all wibbly-wobbly, increase R2.

The Hammond 193T is just about ideal for channels up to 19V. The maximum DC current is 2 amps and I biased my 12V,15V, and 19V prototypes at 1.7A to maximize the distortion performance. If you want to build a Big 24V MoFo, you need the 193V, which is larger, heavier, and more expensive, but it can handle the 2.5A idle current.

If you can find a choke specially wound for audio, that would probably be better still, but it has to handle all the idle current with a little margin. You can try other chokes and inductors too. I tried smaller crossover-type (10mH) air-core and iron-core types. If you try that approach you'll see significantly higher distortion at low frequency, which you might not want, on the other hand, it would make a fine tweeter amp. Ideally, you want your inductor to have low DC resistance so you don't drop a lot of voltage. The iron cores are attractive for this reason. The Hammonds were the best of the handful I tried.

Switching power supplies of the laptop variety come in fixed voltages like 12V, 15V, 19V, and 24V. You need one for each channel. I suggest finding some that are rated for 2 or more times the idle current. You can buy new ones, and there are also some good surplus bargains out there. Some are pretty junky. Be thrifty, but not too thrifty when selecting your power supply.

The device dissipation will be pretty close to your power supply voltage times the idle current. So, for the 19V, 1.7A example, we need a heatsink that can dissipate 32 watts with no more than a 25C rise above ambient temperature. That's .78C/W, which I consider to be the minimum figure. I will award bonus points if you use oversized heatsinks. A lot of beginner projects run into trouble because of inadequate heatsinking, and using big heatsinks just makes life easier.

You should build these as monoblocks. Monoblocks are cool. I built mine on plywood as seen in Figure 11.

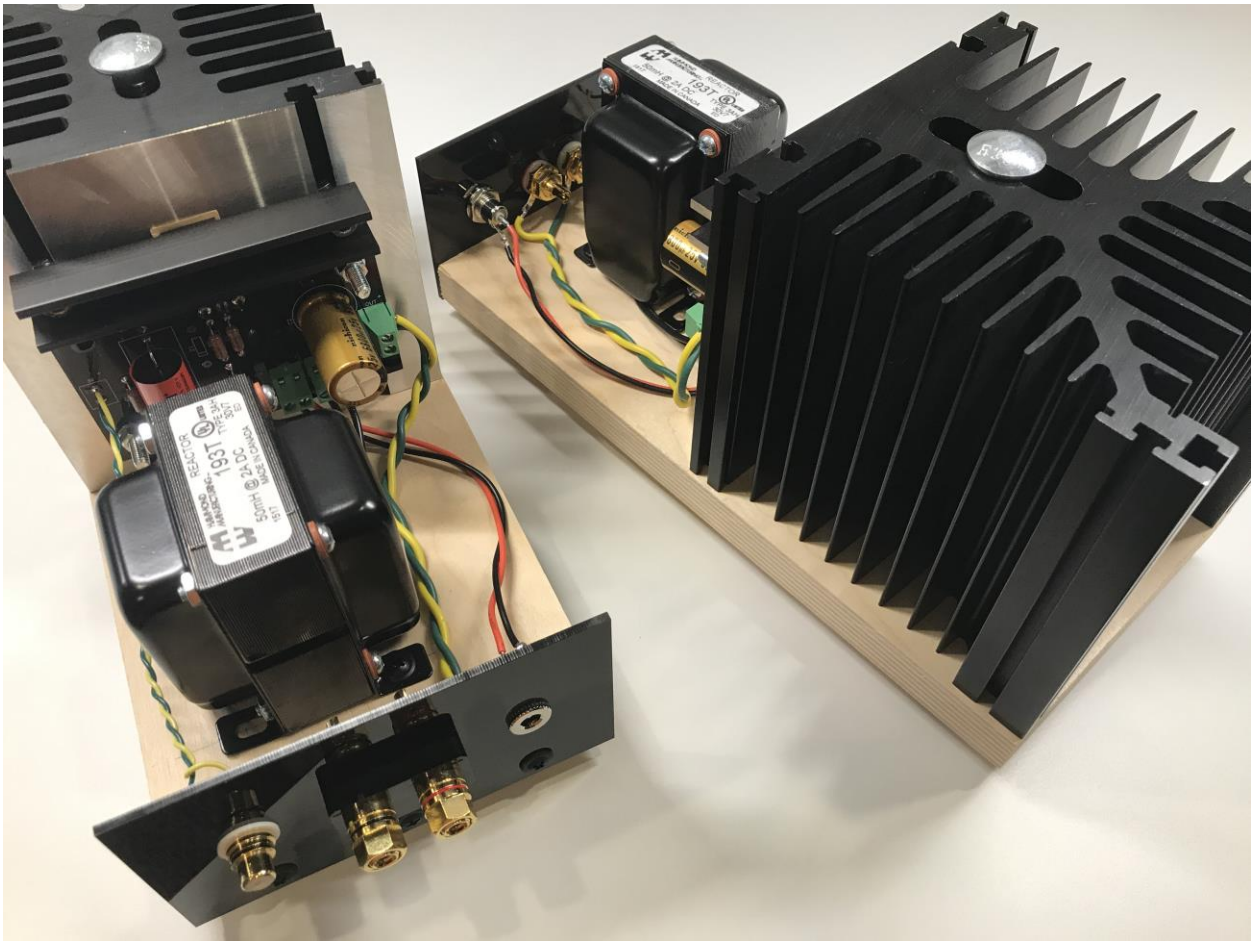

Figure 11

Figure 11 is the single-sided PCB for one channel of MoFo. These should be available for purchase somewhere online soon after this article goes out. These things solder-up very quickly, even if you're a beginner, you should be able build a pair in an afternoon once you have all the parts. Of course, I suggest you take your time and enjoy the building.

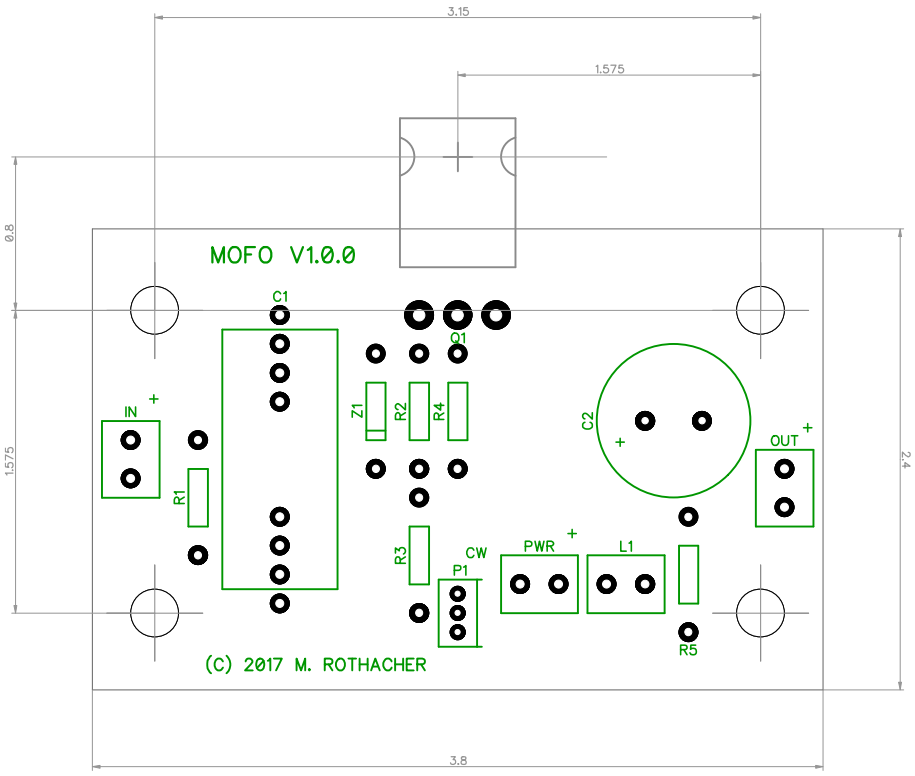

Figure 12

Once everything is assembled, you're ready to adjust the bias. Before you attach the inductors, carefully measure and write-down the DCR of each. The Hammond 193T will be around .6 ohms and the 193V will be around 1 ohm.

Next, adjust P1 for its minimum setting (fully counter-clockwise) and plug in your amplifier channel. You're going to set the bias at around 1.7 amps, unless you're building the big one, which is biased at 2.5A. Measure the voltage across the inductor terminals while you slowly adjust P1 upward. The current through the inductor is the voltage you measure divided by the resistance you wrote down earlier. So, the voltage reading you want is your target current times the DCR. For example, if your DCR is .6 ohms and you want 1.7 amps through L1, you're looking for 1.7 x .6 = 1.02 volts at the inductor terminals.

Alternatively, you can insert a .1 ohm 3W resistor in series with the positive terminal of your PSU and measure the voltage there, e.g. .1 x 1.7 = .17 volts.

Once you set the bias for both channels, you should observe the current for an hour or so, then re-adjust the bias with the channels fully warmed-up. If you're heatsinking is adequate, you should be able to place your hand on the heatsink without discomfort, if only for a few seconds.

Mo MoFo

Since MoFo is a power buffer it's actually a pretty versatile amp. For a comprehensive look at many interesting applications for power buffers, I highly recommend taking a look at the First Watt F4 manual at www.firstwatt.com. It's one of Nelson Pass's most entertaining and informative manuals. A couple I've tried are:

1. You can bridge two MoFo's. In fact, two Big MoFo's gets you close to 100 watts.

2. You can bi-amp with passive crossover networks. I bi-amped my SAL08C08 / Hawthorne Augie open baffles (see Dick Olsher's write-up). A L'Amp DeLux drives the full range and a MoFo drives the Augie. The two make a very nice combination.

So, you wanna know how the MoFo sounds? Well, I'm *biased*, of course, but I think these are more fun than a barrel of monkeys and they sound really good. Paired with a capable preamp (and that's an important caveat), I think you'll be very, very surprised at their transparency, depth, and ability to cast a great big soundstage. You ought to build a pair of these and see for yourself. I plan to expand on this theme in the future, because there's even more fun to be had. I'm working on an assembly video to go with this article and I hope to have that out soon.

Well, that about does 'er, wraps 'er all up. I'd like to thank The Dude for tapping into my subconscious and helping me out. I'm sure he's out there somewhere, takin' it easy for the rest of us, buildin' amps, drinkin' White Russians, and rollin' strikes.

The Dude abides.

Now, I have to go pack for Burning Amp 2017.