**INTRO:** This section is optional and intended for those who understand basic electronics and want to know more about how the O2 works. The previous article covered the design process, while this section describes how the O2 works down to the component level. The schematic is available in a high resolution PDF in the[Resources](http://nwavguy.blogspot.co.nz/2011/08/o2-details.html#resources)section.

**AC POWER SUPPLY:** The wall adapter provides 13.5 – 20 VAC to J1.  D3 is a half-wave rectifier for the positive power supply and D4 does the same for the negative supply. It’s called half-wave because only half the AC cycle is used to alternately charge each of the two supplies. C2 – C5 filter the rough half-wave DC into reasonably constant DC. As long as the bottom of the AC ripple is significantly above the dropout voltage of the regulators, it behaves roughly the same as a more conventional full-wave supply but doesn’t require a center tapped or dual winding transformer. There are four filter capacitors instead of two to further reduce the ripple, provide lower ESR and higher ripple current capability. A classic 7812 and 7912 (U5 & U6), properly grounded, regulate the filtered DC to +/- 12 volts and remove 99.9% of the ripple in the process. C6 and C7 improve the transient response of the regulators by lowering the output impedance at high frequencies. This allows the regulators to “reject” more noise and anomalies making the entire power supply quieter. D1 and D5 block the battery voltage from feeding back into the regulators which would otherwise drain the batteries even when the amp is off. They are Schottky types and only drop about 0.25 - 0.4 volts drop in this application.

**AC WALL TRANSFORMER:** The power supply, with a 13.5 VAC (no load) wall transformer, is right on the edge of letting some ripple though under worst case conditions. If the O2 is used with low line voltage, and for sine wave testing, or using very power hungry low impedance headphones, a higher voltage transformer is recommended (14 – 20 VAC). Some 12 VAC transformers and/or a lower AC line voltage may cause the amp to exhibit higher distortion during low impedance sine wave bench testing as the power supply will fall out of regulation and let AC ripple through the regulators. A 14 - 20 VAC transformer solves the problem (like the WAU16-400 in the parts list). In real world use, the WAU12-200 is the least expensive option and works fine at normal line voltages playing music (not sine waves) into 99% of headphones. The On Semi regulators reach their drop out voltage at about 11.5 VAC loaded. If the amp is driving a low impedance load at high current levels, you need at least 12 VAC loaded (200 ma or about a 60 ohm 5 watt resistor if you want to test a transformer). This doesn’t leave much room for using a 12 VAC transformer if the line voltage is low (below about 117 VAC) hence the primary 14 – 20 VAC recommendation.

**AC CURRENT CONSUMPTION:** While the DC idle current is 20 mA – 24 mA the AC current is higher for several reasons. Two supplies are being generated from a single AC input and the peak charging currents are higher in a half wave supply. There’s also the quiescent current of the regulators, losses in the filter caps, and the battery charging current. Under normal use a 200 mA wall transformer works great. For driving low impedance headphones to high power levels, a 400+ mA transformer is better. Full power worst-case sine wave testing while charging the batteries requires nearly 480 mA RMS of AC current.

**BATTERY POWER:** The batteries are diode isolated by D2 and D6 so they don’t see the full 12 volt supply rails. These are Schottky diodes to maximize the operating voltage when running on battery power. R1 and R2 are 1 watt power resistors. They’re sized to limit the charge current to well under 1/20 of the battery capacity when the batteries are fully charged (around 8 mA with 220 ohms). This prevents overcharging the batteries. And even with the batteries at zero volts, they dissipate well under 1 watt each and limit the maximum current to a safe value (around 50 mA). R1 and R2 can be anywhere in the range of 150 – 270 ohms depending on battery capacity and the intended use. With high capacity batteries and mostly DC operation, use the lower end of that range for faster charging. For mostly AC power, use the higher end to extend battery life on constant charge.

**POWER SWITCH:** S1 is a two pole (DPDT) power switch. You need two poles with two batteries. A simple push on/push off type is specified with a round button to make the front panel more DIY friendly.

**POWER LED:** You might think this doesn’t need a mention but there are some special requriements. First, the normal forward current for most LEDs is 20 mA. That’s as much power as the entire rest of the amplifier needs! So a 20 mA LED would cut the battery life in half. The O2 uses a “HE” high efficiency red LED that is sufficiently visible with only about 0.5 mA. Second, it’s powered symmetrically from the rails (18 – 24 V) on purpose even if that seems less efficient. Otherwise one battery will drain slightly faster than the other. That gets you nothing except mismatched batteries. Finally, the LED’s forward voltage is a critical element of the power management circuit. You can’t change to a different color (especially white or blue) without making other changes as that will require more current and the different forward voltage means the power management circuit has to be altered.

**POWER MANAGEMENT:** The idea is to shut down the amp when the the 9 volt (8.4 volt nominal) batteries drop to somewhere in the 6 – 7 volt range. U2 is a low power comparator. The circuit prevents potentially damaging headphones with DC. The “A” section compares the total power supply voltage to the LED voltage. The LED in this application has a relatively constant drop as the batteries discharge so it forms a “free” voltage reference without any added power consumption or other components. It’s plenty accurate for this application although if you substitute a different LED it may alter the shutdown voltage. C1 removes noise from the battery voltage and also provides a slight turn on delay. When the voltage at pin 2 is higher than pin 3 the comparator output pulls to the negative rail which turns on power MOSFET Q1 and also causes the output of U2B, operating as an inverter, to go high turning on MOSFET Q2. C16 and C21 provide a controlled turn on reducing the transient “click” at power on. If the battery voltage falls too low, or one battery is disconnected, pin 3 will be higher than pin 2 and Q1 and Q2 rapidly switch off shutting down the amp. R25 provides hysteresis to help prevent the amp from turning right back on again as the now unloaded battery voltage rises. Power consumption in shutdown is under 1 mA.

**Q1 AND Q2:** These parts are worthy of a special note. Fairchild makes several suitable MOSFETs for both Q1 and Q2 but many are currently out of stock. I’ve provided substitutes in the parts list that are in stock but some are in a TO220F package rather than the desired, and much smaller, IPAK configuration. If TO220 parts are used they must be the insulated variety (the “F” in TO220F) as they will likely touch each other and possibly touch the adjacent metal battery as well. This isn’t a problem with the smaller IPAK versions the board is designed for. It’s also worth noting these parts must have a Vgs(max) spec of at least 25 volts which is less common and restricts the choices.

**BYPASSING THE POWER MANAGEMENT:** Some might be tempted to bypass the power management circuit entirely and just leave it out for an AC powered desktop O2. This is not a good idea. The power on transient is about ten times greater without the circuit in place. And the on resistance of Q1 and Q2 is so low the drop across them in operation is insignificant (typically < 0.1 V). While the bigger transient may be safe for some headphones, I don’t think it’s worth taking the chance. And if you switch the AC power the transients can be even worse due to the regulators not powering up at exactly the same time. So please don’t blame me if you bypass the MOSFETs and ruin your headphones.

**TURN ON TRANSIENT:**With the power management circuit the turn on transient measures about 800 mV peak (560 mV RMS) into 600 ohms but is very brief at only about 1.5 mS (equivalent to half of one cycle at 330 hz). So it’s a brief click and within even what an iPod Touch can produce playing music and should be harmless. Here you can see the rails (yellow and green) and the output (purple):

**TURN OFF TRANSIENT:**On power off the transient is well under half the above value at only 350 mV peak (250 mV RMS) but much longer at about 20 mS which is the same as a half cycle at 25 hz creating more of a soft “thump”. Into lower impedance loads it’s even less as the remaining energy in the caps discharges sooner. This is also something you can easily get from an iPod playing music and should be harmless:

**POWER SUPPLY FILTERING AND DECOUPLING:** C8 and C9 are low ESR types and provide additional power supply filtering as well as a local low impedance power reserve for musical peaks. Don’t make these caps larger. They’re the optimum value already. They also form the star ground for the amplifier. C17 and C18 are ground referenced 0.22 uF decoupling (bypass) capacitors for the output stage while C10 serves the input stage and is not ground referenced. This is intentional and was the result of testing with the dScope on the first prototype. It eases the ground routing.

**INPUT JACK:** A switched 3.5mm jack (J2) is used to ground the inputs when nothing is plugged in. This isn’t strictly required but is handy to show the O2 itself is silent. Most sources have an output impedance of 330 ohms or less. This limits the input Johnson Noise of the O2, in use, to < 600 ohms. But with the input open circuit, the Johnson Noise of the 10K input resistors (R14 and R20) unrealistically dominates the noise performance and there is audible noise at higher volume settings with sensitive headphones. The input is also more prone to EMI-based hum pickup with an open circuit.

**OFF BOARD INPUTS:** If desired, there’s a 3 pin header (P1) for off board input wiring. If the B3-080 enclosure is used, the input jacks can be located above or below the PCB and the wires can enter P1 from the top or bottom. If off board connectors are used it’s essential to cut the small ground tracks from pins 3 and 4 of J2. Otherwise the inputs will be shorted to ground unless something is plugged into J2. Alternately, you can leave J2 off the board entirely (and delete the hole from the panel). Ideally off board jacks should be isolated from the chassis and only grounded at the P1 header using twisted pair or shielded wiring kept away from the power supply and output stage.

**INPUT TERMINATION & FILTERING:** R7 and R3 serve multiple purposes and can be any value from 100 ohms to about 330 ohms (normally they can be the same value as the high gain resistors R19 and R23—i.e. 274 ohms). They provide series input current limiting protection for U1 for when the amp is powered off or the inputs are overloaded. They also form an RC filter with C11 and C12 to prevent significant RF from making it to the op amp inputs where it could be demodulated and create excessive DC and noises. And finally they enhance the ESD capability of the amp. R14 and R20 set the input impedance to 10K which, as discussed in the last article, is optimal.

**GAIN STAGE:** U1 operates as a non-inverting amplifier for each channel. The crosstalk between the sections is better than –110 dB (I measured it) so there’s no benefit to using single op amps. R16 and R22 were chosen to keep the impedances low to reduce Johnson Noise but not excessively load the amplifier increasing THD. This is one area where things get tricky if you’re “op amp rolling” and testing many op amps in a given circuit. Some low power op amps would work better with higher values for R16 and R22 (and the other 4 gain resistors). For the [Low Power](http://nwavguy.blogspot.com/2011/08/o2-details.html#lowpoweroption) version of the O2 using the OPA2277 feedback resistors of 1.5K still work but doubling all the gain resistor values (i.e. ~3K for R16/R22, 2K for R17/R21, etc.) to reduce the load on the low power op amp at the expensive of slightly higher noise. Ideally C19 and C20 should be reduced to 100 pF if R16/R22 are 3K to maintaint roughly the same compensation pole frequency.

**GAIN** **SWITCH**: S2 switches the ground resistors in the gain stage feedback loop. That way if the switch is briefly open circuit the amp won’t slam into a supply rail from opening the feedback loop. It just drops to 1X gain. All the routing is kept as short as possible and by switching the ground resistors the parasitic values and crosstalk are less of an issue.

**GAIN STAGE LIMITATIONS:** The overload level of the input stage is directly related to the power supply voltage. When running from AC power it’s very unlikely to be a problem at realistic gain settings. But for portable use you have to pick a reasonable battery voltage to use for the calculations. Looking at the curve below at 0.1C (27 mA for this battery which is very close to the typical consumption of the O2 in use) even at 8 hours the battery voltage is still about 8.6 volts (graph courtesy accupower-usa.com):

The battery finally starts to seriously die at about 9 hours when it hits 8.5 volts. Using that value, the input stage starts to clip at 4.6 V RMS. Here’s it’s shown at 4.55 V RMS with the actual rails to the NJM2068 shown in yellow and green at 8.25V. The exact measurements are shown below the traces and the rails are lower due to the ~0.25V drop across D2 and D6:

The maximum input gain would be 4.5/Vinmax. So for a 0.5 V iPOD LOD you get 4.5/0.5 = 9X. For the 1.4 V RMS AMB gamma USB DAC it’s 4.5/1.4 = 3.2X. Here’s the O2 input stage on AC power:

Above you can see 7.1V RMS. *So the max gain is 7/Vinmax*. Now the max gain with the 1.4V RMS gamma DAC is 7/1.4 = 5X (14 dB).

**EXCESS GAIN:**On AC power you can figure out the excess gain available using 20\*log( 7/V110db ). So if your headphones hit 110 dB at 0.5 volts it’s 20\*log(7/0.5) = 23 dB. For the HD600/650 it’s 20\*log(7/2.3) = 9.6 dB. On battery power it’s 20\*log( 4.5/V110db ) and the HD600 still has 6 dB of excess gain available (half the volume control’s range with the “3B” taper). The HD600 is about at the limit of what most portable amps, like the Mini3, can even drive and the O2 still offers 6 dB of excess gain beyond that running from nearly dead batteries.

**GAIN STAGE OP AMP:** I dScope tested nearly two dozen op amps in developing the O2 (for the gain and output stages). See: [Op Amp Measurements](http://nwavguy.blogspot.com/2011/08/op-amp-measurements.html). One of the biggest surprises was *a $0.39 part essentially matched the most expensive op amps I tested*! And it may surprise some to know it’s made by JRC and isn’t their version of the venerable 5532 (which also performed well but costs more, is noisier, and uses more power). The NJM2068 is dead quiet, has vanishingly low distortion, and uses less power than lots of other parts I tried including the popular OPA2134. At moderate gains and with typical headphone loads the output stage dominates the distortion not the NJM2068. So improving the NJM2068 doesn’t significantly change the total performance. And even measuring just the gain stage the NJM2068 challenges the measurement limits of the dScope in some tests. At higher gains (> 4X) there’s a small reduction in high frequency distortion using the NJM5532 instead of the NJM2068 but it costs more, has 3 dB more noise, and raises the total idle current by 13% to around 25 – 27 mA. For those who are worried about 0.0018% vs 0.0010% at 10 Khz, and don’t care about battery life, the NJM5532 is the better choice. Anything more expensive is a waste of money and might perform worse due to needing different compensation, impedances, power supply treatment, etc.

**OP AMP “SOUND”:** This is discussed more in [Op Amp Myths](http://nwavguy.blogspot.com/2011/08/op-amps-myths-facts.html), the [Design Process](http://nwavguy.blogspot.com/2011/07/o2-design-process.html) article, and the [first article](http://nwavguy.blogspot.com/2011/07/o2-headphone-amp.html). In a proper application where the op amp is being used as intended it’s been widely shown op amps that measure well in circuit don’t have a detectable “sound”. The “sound” others claim to hear is either from incorrectly using the op amps (which will show up with the right measurements) or it’s the usual [subjective bias](http://nwavguy.blogspot.com/2011/05/subjective-vs-objective-debate.html) of sighted listening—i.e. [their brains are deceiving them](http://www.youtube.com/watch?v=G-lN8vWm3m0). The NJM2068 measures extremely well in this application, so I wasn’t surprised when none of us could tell the O2’s sound quality from the Benchmark DAC1’s headphone output in blind listening..

**ADDITIONAL COMPENSATION:** C19 and C20 work with the 2068’s [dominant pole compensation](http://en.wikipedia.org/wiki/Frequency_compensation#Dominant-pole_compensation) to optimize the stability and transient response. Their value (220 pF) might seem large to may who are used to seeing 22 pF or less in other designs but that’s mostly related to the 1.5K value of R16 and R22. If R16 and R22 are increased to 3K in the lower power version C19 and C20 should be reduced to 100 pF. If the resistors were ten times greater (and they often sadly are) C19 and C20 would be ten times smaller. Compensation is discussed more in the [Design Process](http://nwavguy.blogspot.com/2011/07/o2-design-process.html) and [Op Amp Measurements](http://nwavguy.blogspot.com/2011/08/op-amp-measurements.html) articles.

**VOLUME CONTROL:** U1 directly drives VR1 which is a 10K Alps RK097 audio taper pot designed for volume control duty. C13 and C14 isolate the input DC bias current of U3 and U4 from the volume control eliminating the “rustling” noise you get when changing the volume in many amplifiers like the Mini3 and FiiO E9. If you remote mount the volume control use twisted pair or shielded wiring with the ground(s)/shield(s) terminated at the volume control pads on the PCB. The twisted pairs can be removed from CAT5 wire (leaving them tightly twisted) and work well for such wiring.

**VOLUME CONTROL LOCATION & GAIN STRUCTURE:** The volume control was intentionally placed “in the middle” between the two stages for some very good reasons. The primary benefit is it dramatically improves the noise performance of the O2. See [Section 2-11 in the Design article](http://nwavguy.blogspot.com/2011/07/o2-design-process.html#circuitdesign).

**DC BLOCKING:** C13 and C14 are high quality 2.2 uF film caps rated for coupling applications. I’ve tested 4 different caps and found no significant difference between them including analyzing the “ differential signal” (or lack thereof) directly across the capacitor during operation as well as more usual tests like THD sweeps. The default Kemet MMK caps are designed for signal coupling and do an excellent job. There’s also a couple Wima part numbers listed for those who are “brand name” conscious and don’t mind spending a bit more. I also tested an Epcos cap that also performed very similarly. The fourth was an expensive audiophile grade Wima MKP polypropylene that would never fit in the case that I tested only for comparison. But, just as Doug Self and others have documented, it didn’t perform any better in this application. All the caps had only a really tiny *linear* differential signal related to their ESR. Another myth busted and discussed more in the [Design Process](http://nwavguy.blogspot.com/2011/07/o2-design-process.html) article.

**R12 & R13 TRADE-OFF:** R12 and R13 provide DC bias for the output op amps. Their value wants to be large to push the low frequency roll off from the C13 and C14 down close to DC. But their value wants to be small to minimize DC offset at the headphones. So it’s a classic trade off. Larger value film caps also take up more space and are more expensive. So 1 uF caps with 100K would be cheaper but the amp would have over twice the DC offset. I opted to go the more expensive route at around 40K and 2.2 uF. This means – 3 dB at only 1.8 hz and results in a typical DC offset of under 4 mV—both excellent specs.

**OUTPUT STAGE:** To me, this is the best part of the O2. If you would have asked me if a $0.60 op amp could crank out well over 140 mA of peak current at seriously low levels of distortion into the lowest impedance loads I would have had some serious doubts. For that kind of performance you’re *supposed*to buy a $24 pair of big TO220 buffers like the TI/Burr Brown BUF634. But those clever folks at JRC had other ideas with the NJM4556 (also called the JRC4556 or NJR4556). They took a better than decent audio op amp and seriously upgraded the output stage. The result works way better than most would ever guess. The trick here was to *parallel the two devices in each IC* and use a dedicated IC for each channel. This has numerous benefits including twice the peak current capability, better channel isolation from the high currents involved, lower distortion, twice the thermal dissipation and more. More on the dissipation can be found a few paragraphs down but it turns out you really do need two ICs.You can just compare the [O2 measurements](http://nwavguy.blogspot.com/2011/07/o2-headphone-amp.html) to the [Cmoy measurements](http://nwavguy.blogspot.com/2011/07/cmoy-with-gain.html" \t "_blank) and you’ll see the difference (although there’s more going on between those two). There’s also more information about the output stage in the [O2 Design Process](http://nwavguy.blogspot.com/2011/07/o2-design-process.html) article starting around section 2-12.

**CURRENT LIMITING & HEADPHONE PROTECTION:** A welcome bonus with the NJM4556 is the current limiting is about perfect. Two sections in parallel current limit about 20% above the 166 mA max current goal calculated in the [Design Process](http://nwavguy.blogspot.com/2011/07/o2-design-process.html) article. This helps prevent accidental headphone damage into low impedance loads compared to amps with current limits more fitting for an arc welder. And some amps without any current limiting blow up if their outputs are even briefly shorted (which happens just plugging a pair of headphones in). Not so with the O2. The NJM4556 seems rather tolerant of at least brief abuse and the current limit might save some low impedance headphones from being destroyed if someone accidentally uses the wrong gain setting, etc. Other amps with higher current limits can deliver more than 1000 mW into low impedance loads which is far in excess of the safe limits specified for most headphones.

**PARALLEL OP AMPS:** Op amps are paralleled all the time. It can lower their noise under some circumstances and increases their current and power dissipation capability. I’ve seen lower current op amps paralleled for headphone duty, but I’ve never seen the 4556 in parallel. If someone knows of a published design that predates this one, please let me know?

**CURRENT SHARING & OUTPUT IMPEDANCE:** The two op amp sections on a given silicon die within a single package tend to be fairly well matched. But it’s still a good idea to provide some isolation and series resistance so they will more equally share the load current and not fight each other due to differences in DC offset. This series resistance also improves stability. I did the math, and tried a half dozen different 4556’s, and concluded 1 ohm works well giving an output impedance of around 0.5 ohms. If you don’t mind a slightly higher output impedance, you can go up to 4 ohms if you want even more isolation, a bit more short circuit protection, and less DC offset current (see the next paragraph) and still stay under the “1/8 rule” for 16 ohm headphones. For 32 ohm headphones you could go up to 8 ohms each. See: [Output Impedance](http://nwavguy.blogspot.com/2011/02/headphone-amp-impedance.html). Because the NJM4556 op amps have beefy output stages and are operating with maximum feedback their output impedance, without the resistors, is under 0.1 ohms.

**DC OFFSET DIFFERENCES & QUIESCENT CURRENT:** Because they’re on the same die, the two op amps in each 4556 tend to be fairly well matched for DC offset. But if one is say 2mV and one is 4 mV, that creates (0.004 – 0.002) / 2 ohms = 1 mA DC current between the two amplifiers. Such a low value value of current doesn’t significantly change the distortion performance of the 4556 but it does increase the idle current of the O2 by 1 mA. This is most significant in the [Low Power](http://nwavguy.blogspot.com/2011/08/o2-details.html#lowpoweroption) version where it’s about a 15% change. Hence*I suggest increasing the isolation resistors (R10, R11, R15, R18) to 6.8 ohms in the lower power version to minimize this current*. Because the Low Power version is only recommended for loads of 32 ohms or higher  the output impedance can safely be as high as 4 ohms with no ill effect. 6.8 ohm isolation resistors result in a 3.2 ohm output impedance which is safely below 4 ohms. This will significantly extend battery life if there are significant DC offset differences.

**SHORT CIRCUITS:** Headphone plugs create a brief short when inserted and removed. That’s why you read everywhere to always turn down the volume before doing either. I’ve tested the O2 for damage with such shorts and I haven’t had any problems. But a sustained short, or one at a very high level, could damage the 4556 op amp. But even the expensive output buffers have cautions on their datasheets about short circuit damage as their thermal protection may not be fast enough to save them. It’s a common trade-off in headphone amp design. Many amps are far more fragile than the O2. But if it’s something you’re worried about, I would suggest increasing R10, R11, R15 and R18 to 1/4 your minimum headphone impedance. So for 300 ohm headphones, use approximately 75 ohm resistors. This will improve the odds the O2 will survive more severe short circuits.

**JRC:** For those into designer labels JRC deserves some explanation. JRC doesn’t get much respect in audiophile circles. Based on the O2’s performance, however, those audiophiles might be foolish to dismiss this audio-centric company. For what it’s worth, JRC is more focused on analog audio applications than any of the other mainstream suppliers. Even Analog Devices tends to focus more on digital, high speed stuff, A/D, D/A, etc. Some interesting JRC trivia:

* **Lower Cost Industry Standard ICs** – They make their own versions of a lot of bread and butter analog ICs. For example they have their own version of the most popular audio op amp on the planet—the 5532 originally developed by Signetics. And the NJM2903 low power comparator in the O2 is their less expensive version of the LM2903 from National. In my experience these parts work very similarly to the ones they’re based on but almost always cost less. This might help explain why some audiophiles see JRC as the “WalMart” of chips (lower cost versions). But… keep reading!
* **Application-Specific ICs** – JRC’s strength is offering ICs nobody else offers. A big company, like say Denon, might approach JRC to make a very specific IC that Denon needs in large quantities. Such chips are common in the digital world, but much less so in the analog world. And even better, JRC often adds these application-specific parts to their regular offerings and anyone can buy them.
* **NJM4556** – I don’t know this for a fact, but rumor has it the 4556 used here was originally an application-specific part designed for, ta da, driving headphones! It’s a unique op amp. Nobody else makes anything much like it. JRC is not the best at marketing, their datasheets are kind of ho-hum (probably partly because of the Japanese-to-English language issues), but the O2 proves their parts, including this one for under $0.60, can work *very* well and fill critical niche markets.

**OUTPUT CIRCUIT & STABILITY:** As explained in the last article, the goal was not to use any distortion inducing output inductors or ferrites. The O2 achieves that goal five ways: Dominant pole compensation, additional compensation, a two stage design (see the [Design Process](http://nwavguy.blogspot.com/2011/07/o2-design-process.html) article), proper board layout and power supply/ground scheme, and the 1+ ohm output resistors on each of the four op amps. I tested the stability in the [first article](http://nwavguy.blogspot.com/2011/07/o2-headphone-amp.html) with several reactive loads including added capacitance without even a trace of ringing or instability.

**POWER CONSUMPTION & DISSIPATION:**If you do the math (see [Burr Brown's SBOA-022 appnote](http://www.ti.com/litv/pdf/sboa022)) for the target goals of voltage and current (see the [Design Process](http://nwavguy.blogspot.com/2011/07/o2-design-process.html) article) the power dissipation playing music under worst case conditions is around 700 mW per channel. If you tried to use a single IC, like the AD8397, for both channels it would get too hot and likely fail with 1.4 watts total dissipation. But *two* DIP8 devices can handle 1.6 – 2.0 watts. I've monitored the O2's power consumption versus time using a differential scope connection across a current shunt playing real music with various loads. Worst case clipping music into 15 ohms, the entire amplifier only consumes about 60 mA of average power or about 1.5 watts when running on AC. And it's rare the 4556 ICs rise above 40C case temp. If you subtract what's going into the load and used by other parts of the circuit, each NJM4556 is dissipating less than 700 mW even under the most extreme conditions using music. I've run the O2 at full power into 15 ohms with sine waves for several seconds at a time and haven't noticed any changes in its measured performance let alone had any failures despite the fact the dissipation per channel is (briefly) over 2 watts. I suspect this exceeds the ideal SOA (Safe Operating Area) of the output stages in the chip. *That's why there's a warning in the*[*Cautions*](http://nwavguy.blogspot.co.nz/2011/08/o2-details.html#cautions)*section about sustained sine wave testing into low impedance loads.* The O2 is designed for real world use. If you sufficiently abuse it with test signals into loads below 150 ohms you might damage it.

**HIGHER VOLTAGE SUPPLY RAILS:** There have been several suggesting higher voltage supply rails for various reasons. Some have dredged up rare discontinued headphones that need more than 7 Vrms to hit 115 dB SPL and others have suggested it as a way to increase the input stage overload point. The problem is in the above paragraph. Output stage dissipation goes up as the square of voltage. Increasing the rails from 12V to 15V increases the 700 mW dissipation with music to about 1100 mW which is more than any DIP-8 (or SOIC-8) device can safely handle unless you like to live dangerously. And please keep in mind if the op amp does fail it will likely dump massive DC into your headphones potentially taking them with it. I don’t believe that’s a risk worth taking. My suggestion for the 0.1% of cases that really need more voltage to simply use another amplifier that has higher dissipation ability.

**PCB BOARD LAYOUT:** The O2 is a bit cramped and getting a decent layout was challenging. It’s very much function over form and designed to *work* well not look nice. The tests show it’s reasonably “electrically symmetrical” meaning both channels perform very similarly. The [Design Process](http://nwavguy.blogspot.com/2011/07/o2-design-process.html) article went into a lot of things to consider when laying out a PC board. In a perfect world I wouldn’t have warm parts like the regulators near electrolytic caps for example but that only means the caps might last 20 instead of 25 years with typical use. The alternative would have meant compromising the power and ground distribution. The ground reference for the regulators is essentially part of their feedback loop and important to the performance of the power supply and entire amp. Many similar decisions were made with the PCB design including the front panel layout.

**LOW POWER VERSION:** Part of testing the nearly two dozen op amps was measuring the power consumption of the O2 with the various op amps installed. The datasheets often supply a range of quiescent currents and often at the wrong power supply voltage. Real world conditions (9 volt battery power, loading on the amp, etc.) often change the value. All but ~1 mA of the O2’s 20 - 24 mA idle current is the audio circuitry and 95% of that is the quiescent current of the 6 individual op amps. So focusing on the op amps was clearly the main key to improving battery life. Here’s what I came up with that results in about triple the battery life by dropping total idle current to 6 – 8 mA:

* **OPA2277** - This Burr Brown/TI part for the gain stage requires only 0.8 mA per op amp, has low noise and the slew rate is plenty fast. It has a bit more high frequency distortion than the NJM2068 but it’s still low enough for gains of 7X and lower. The main drawback is the price: $4.65 vs $0.39 for the NJM2068.
* **TLE2062** - This one was tougher. The requirements: High current output (> 40 mA), 24+ volt power supplies, through hole (not surface mount), low noise, low distortion, short circuit protected, and lower quiescent power than the NJM4556. Amazingly, the TI TLE2062 meets all of these requirements with less then 0.4 mA of quiescent current per amp. And they’re only $3 each which isn’t too bad. It’s rated at an impressive 80 mA max current, but as you’ll see, it doesn’t quite manage that at low distortion.
* **Mix & Match?** - You *could* use just one or the other. But the OPA2277 won’t buy you much more battery life by itself. And the TLE2062s dominate the amp’s distortion performance so using the NJM2068 in the gain stage doesn’t improve things. So they’re much better as a pair or not at all.

**LOW POWER DISTORTION & OUTPUT:** As mentioned above, there are some trade offs. I don’t recommend the low power version for loads less than about 32 - 50 ohms. The graph below is running from battery power for all tests. The TLE2062 degrades the Low Power (LP) O2 to roughly Mini3 performance into 15 ohms (red vs pink below). Into 150 ohms, however, the LP O2 blows the Mini3 away in max power with 167 mW into 150 ohms vs 38 mW at similar levels of distortion. The standard O2 (light blue bottom trace) is still significantly better. And finally, the brown trace is the LP O2 into 600 ohms showing the OPA2277/TLE2062 pair has respectable performance (0.001% at 1 volt) when the output stage isn’t dominating the overall distortion (And for the eagle-eyed geeks, the LP plots started at 10 mV which is they the look much better at the far left—I’m doing this on all future plots):

**LOW POWER VERSION NOISE:** Low power op amps are usually more noisy, and that’s true here. This result is about 6 dB worse than the default version but still better than almost every other headphone amp I’ve measured. As explained elsewhere this is barely audible at full volume with the UE SF5s. The two stage design helps a lot regardless of the op amps used, and the OPA2277 has very impressive noise specs considering it’s very low power. Here’s the noise referenced to the usual 400 mV at a worst case full volume: