EL-10A-1 400 Watt Electronic Load

EL-10A-1
400 Watt, 3 to 40 VDC, 0 to 40 ADC Electronic Load

Compact Electronic Load for design and testing of power supplies, batteries, solar power systems, DC power distribution systems, rectifiers and more.

Conservatively rated Load is capable of 400 Watt and 40 Amp continuous duty. Features include:

- individually set-able high and low current settings over entire 40 Amp range,
- constant current and fixed resistance modes,
- modulation capability over 10 Hz to 100 KHz, and
- internal Voltage and current meters with external current monitor point.

Thermostatically controlled 100 CFM fan allows quite operation at low power levels yet sufficient cooling for a continuous 400 Watt load.

EL-10A-1 400 Watt Electronic Load

Characteristics:

Input Voltage Range	3 to 40 VDC (0.7 to 3 VDC has limited, but stable VI capability as specified in “Current Setting”)	Current or Resistance Mode
Input Current Range	0 to 40 ADC	
Power Dissipation	400 W (maximum steady state) or DC SOA - see Fig. 1 for duty cycle limited performance.	
Current Ranges	1, 2, 4, 10, 20, 40 ADC	Constant Current Mode
Current Setting	Two 10 turn precision potentiometers High Current 0 to 40 ADC (or range maximum) Low Current 0 to 40 ADC (or range maximum) Resolution 0.1 ADC per turn to 4 ADC per turn Regulation Better than 0.1% (3 to 40 VDC from 0 to 40 ADC) Better than 0.5% (2 to 3 VDC from 0 to 30 ADC) Better than 0.5% (0.7 to 2 VDC from 0 to 20 ADC)	
Current Step (Transient Load)	Steps between Low and High Current settings for any values of either Slew rate > 8A/μS or 8000 kA/Second at 40 ADC 3 to 40 VDC > 6A/μS or 6000 kA/Second at 10 ADC and 6 VDC > 1.6A/μS or 1600 kA/Second at 10 ADC and 1.5 VDC Pulse Width 50 μS to indefinite (DC level) Control External 50 Ohm Generator (0 to 5V) or panel mounted “Load Current Step” switch	
Modulation	External 600 Ohm Generator Level -60 to 0 dB Freq. 10 Hz to 100 KHz (-6 dB points) Signal Sine, triangular, saw-tooth, pulse, square (limited to above freq. range spec.)	
Resistive Load	Resistive Load set by 10 turn precision potentiometer (over 100:1 range) Ranges 0.1 to 10 Ohm 1 to 100 Ohm 10 to 1000 Ohm Regulation Better than 1% (1.5 to 40 VDC) Stable to 0 VDC Resistive Load can be set, in the Load Off condition, and read directly in Ohms on the internal panel mounted Voltmeter ***Caution: Do not exceed the SOA when setting Load Resistance - the above ranges allow it but the Load transistors may be destroyed.***	Resistance Mode
Current Meter	Displays Load current in either the Resistive or Current Modes and also displays the Load Current setting prior to turning the load on. **Ranges** **Resolution** 2 A 1 mA 20 A 10 mA 200 A 0.1A Accuracy Better than 1% or ± 1 digit (all conditions and ranges)	Current or Resistance Mode
Volt Meter	Reads Load terminal voltage in the Internal mode or the voltage at the external measurement jacks in the External mode; **Ranges** **Resolution** 200 mV 0.1mV 2 V 1mV 20 V 10mV 200 V 100mV Ohms (in the Resistive Mode) - ranges set by Load Accuracy Better than 0.1% or ± 1 digit (all conditions and ranges)	

Characteristics: (Continued)

External Current Monitor	Terminate into 50Ω for viewing DC or high frequency characteristics of Load current. Scale factor 5 mV per Amp terminated (or 10 mV per Amp OC) Response Better than 1% (DC to 10 MHz terminated)	
Poteniometric Voltage	Allows offsetting Volt Meter for improved resolution when measuring changing Voltages (such as load, line or temperature effects) Set by 10 turn precision potentiometer, with overlapping ranges Ranges 10V (0 - 14 VDC) 20V (8 - 21 VDC) 30V (18 - 31 VDC) 40V (28 - 40 VDC) Stability Better than 100 ppm over 24 hours and any load Resolution ± 0.1 mV equivalent to 5 ½ digit Voltmeter on 20 V Range	Current or Resistance Mode
Input Power	105 to 125 VAC, 50/60 Hz, 25 VA (max) NEMA 5-15P Cord set 1 Amp GMA fuse and on/off switch mounted on rear panel	
Cooling	Thermaloy 16073 11" heat sink and 100 CFM, thermostatically controlled 115 VAC fan **- Do Not restrict airflow -** Thermal time constant: 15.5 °C in 10 minutes at T_a = +25 °C and 400 Watt dissipation Derate to 200 Watts at T_a = +40 °C, below 5000 feet elevation and 50% RH	

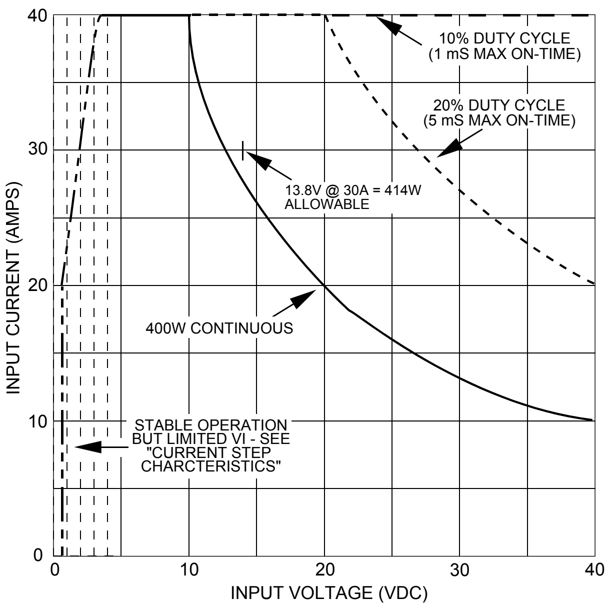


Fig. 1. EL-10A-1 SOA (safe operating area).

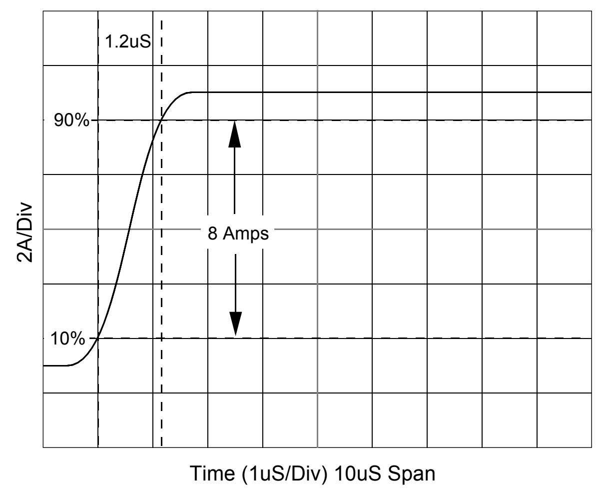


Fig. 2. EL-10A-1 Typical Load Step (Transient response), Input Voltage = 6 VDC, Step = 0 to 10ADC, 2" leads Load to Battery. Response represents 6.7A/uS or 6700 kA/S.

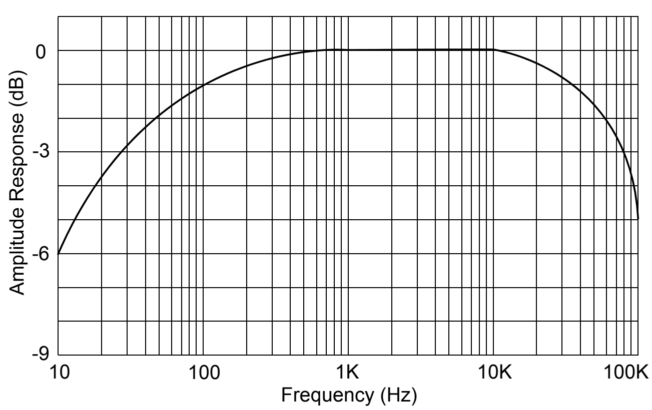


Fig. 3. EL-10A-1 External Modulation Frequency Response.

Basic Operation:

The EL-10A-1 operation can best be explained in the context of its' applications. Expanding upon the "Characteristics" section, the operation of the various controls, inputs, outputs and monitoring will enhance operational understanding.

Initial turn on. The EL-10A-1 has an AC Power switch and GMA fuse mounted on the rear panel. Standby power is approximately 1.5 VA, so there is little need to turn it on and off during the day while in use. When the cooling fan is on (thermostatically controlled) the input power is less than 25 VA.

A common application is power supply testing, so in that context, the 0.25" Brass connectors - labeled "Load Input, Pos and Neg" - provide for connection to the UUT (unit under test). The leads used for this should be as large as practical for the load current expected, short as possible and ideally parallel conductors (zip cord).

Voltage monitoring. The UUT voltage can be read on the internal DPM (digital panel meter) with the "Voltmeter" switch in the "Internal" position and will provide adequate readings for functional tests. For performance testing, the "External" position should be used with a Kelvin connection. That is, the "External" jacks should be used to connect leads directly to the UUT output terminals avoiding erroneous readings due to Load lead drop.

The DPM ranges provide good resolution and accuracy from 0 to 200V. The "Poteniometric Voltage" set in ranges by a 10 turn pot, allows the Voltage being measured to be offset. If for example, the load regulation of a 13.8 VDC power supply is to be determined, the 20V range only allows 10 mV resolution, however if the poteniometric voltage is adjusted to 13.7 VDC, the input to the DPM will only be 0.1 VDC which measured on the 200 mV range will provide 0.1 mV resolution, or the equivalent of a 5 ½ digit meter. While this does not improve the basic 0.1% accuracy, it does improve the resolution for measuring Voltage changes. **Caution:** For normal voltage measurements ensure the "Poteniometric Voltage" switch is in the OFF position.

Selecting the Load. To load the UUT, a selection is made using the "Load" switch. Normally in the "Off" position, this switch allows the operator to select between constant current load or fixed resistance load.

Resistive Load. In the fixed resistance mode the "Resistive Load" switch is used to select the applicable range and the "Resistance" pot is used for exact value selection, and while inherently non-linear, the adjustment has good resolution. The effective Load resistance can be read on the Voltmeter with it's range switch in the "Ohms" position and the "Load" switch Off. Once the resistance is set, the Voltmeter switch should be set to an appropriate range for the expected Load Voltage - otherwise it will over-range when the "Load" switch is turned On.

Caution: Do not exceed the SOA when setting Load Resistance - the ranges allow it but the Load transistors may be destroyed.

Constant Current Load. In the constant current mode, several options are available. The "Step" switch selects "Low Current", "High Current" or "Auto". The "Low Current" and "High Current" adjustments are identical and are made with the appropriate 10 turn precision pot. Either can be set to any value of current from 0 to the maximum range set by the "Range" switch; 1, 2, 4, 10, 20, or 40 ADC.

The Current Meter has three independent ranges; 2, 20, 200 ADC which provide resolution comparable to the Load Current Range selected. As well, the "Amp Meter" switch allows the load current to be set prior to actually applying it to the UUT. In the "Load Set" position the Amp Meter will display the Load Current setting that will be used to load the UUT when connected. In the "Load Only" position the Amp Meter will only display the actual load current.

When performance is to be evaluated at a low and high current, it is convenient to set the two values and switch from one to the other. In the "Auto" position an external 0 to +5V pulse will electronically switch from "Low" to "High". The "Load Step Input" is optically isolated but DC coupled, so either level can be held indefinitely. The minimum practical pulse width is 50 μS.

The SOA (safe operating area) curves presented in "Characteristics" shows continuous operation is allowed at 40 ADC for Voltage levels up to 10 VDC above which the 400 Watt contour must be observed (DC SOA). However, for pulse operation 40A currents can be sustained up to 20 VDC with a maximum 5 mS pulse duration and 20% duty cycle, or 40A currents up to 40 VDC with a maximum 1 mS pulse duration and 10% duty cycle.

To set current levels outside the DC SOA it is necessary to use the "Amp Meter" switch to select the "Set/Load" option. This allows the current levels to be set with the "Load" switch Off by reading the set point values on the Current Meter. When the "Load" switch is set to "Current" mode, the Current Meter will read the actual Load current. ***Use Caution outside the DC SOA - the Load transistors can be destroyed if any SOA curves are exceeded.***

Load Step (Transient Response). Transient response of the UUT can be evaluated by observing the Load current pulse using a 50Ω BNC cable connected from the "Current Mon Out" to a 50Ω load at the input of a dual channel oscilloscope. The second channel should be connected directly to the output terminals of the UUT - not the Load - using acceptable high frequency practices. ***Do not underestimate the effects of interconnecting wires*** - even though a DC power supply is under test, RLC values associated with the interconnects are not negligible.

External Modulation. Further UUT stability tests can be performed using the "Ext. Modulation" input. A signal or waveform generator can be used to modulate the Current mode. The generator should be set to -60 dB and 600 Ω and the "Ext. Modulation" switch used to turn modulation on and off.

The Load current at which the modulation is desired should be set as normal and then the generator level adjusted for the desired peak to peak current as observed on the oscilloscope (set up as above). The control loop can now be swept from 10 Hz to 100 KHz to compliment the pulse testing stability. Also, this allows an easy method for measuring the UUT's output impedance vs frequency, which is simply the AC Voltage at the UUT's output terminals divided by the AC modulation current.

Theory of Operation:

Introduction. The EL-10A-1 provides a convenient way to test a power source under load, and is actually fairly simple, even though the numerous options tend to complicate it somewhat.

Refer to the schematics “Monitor and Control” and “Power Supply and Poteniometric Source” to follow theory of operation.

Internal Power Supply. Very little power is required by the EL-10A-1 because its’ fairly large transistor drive current is derived from the power source under test. In order to use distributor stock parts, two small PC mounted transformers are used to provide the required DC operating Voltages.

Incoming AC line Voltage is applied to the primaries through S1 and F1, rear panel mounted Fuse and Power Switch that also provide AC line voltage to S2, a 49^{o}C normally open thermal switch, and in turn M1, a 100 CFM cooling fan.

T202 provides two isolated, zener diode regulated, 9 VDC outputs to operated the Voltage and Current DPMs. These DPMs have a small common mode range that does not include the power rails. So their power source be isolated from the measurement inputs.

T201 provides all of the operating voltages required for the “Monitor and Control” board and associated panel mounted controls. A full-wave bridge rectifier and filter capacitor provides 24 VDC that is zener regulated by D207 and D208, using a split connection, to produce +10 VDC and -10 VDC. The 24 VDC is also used to power D1, a green “Power On” LED, and D2, a yellow “Load On” LED. D2 is controlled by the “Load” switch to indicate when the EL-10A-1 load is actually connected to the UUT.

U201 regulates +5 VDC for the analog switching function, used in both manual and automatic operation. The very effective monolithic regulator minimizes switching noise and artifacts possible in this mode.

Poteniometric Source. This is the other major function of the power supply. A Voltage doubler, D205, D206, C207 and C208, provides an isolated 48 VDC using the second winding of T201. A shunt-regulator produces a very stable 42 VDC from this source.

Q201 and Q202 form a classic constant current source that allows maximum utilization of the 48 VDC source while limiting power dissipation in Q203, the actual control element of the regulator. Q202’s base bias current is used to power U202, a precision 2.5 VDC reference and U203, a low power rail-rail CMOS Op Amp.

U203 uses feedback to control Q203 producing a very stable 42 VDC output that is fixed by the ratio of (R210/R209 + 1). This output is scaled by S3 and adjusted by R4 to provide a very stable offset Voltage that can be used to extend the resolution of the internal Voltmeter. Short term stability is typically 10 ppm for light loads or 100 ppm for full load over 24 hours. This provides a reference with a stability better than 0.01% per day.

The power supply is Assembly EL10A102 and fully contained on PWB EL10A122 which is mounted vertically on the heat sink extrusion. Component designators are in the range of 201 to 299, noting they belong to Assembly xxxxx102.

Monitor and Control. This function consist of the Monitor and Control Assembly EL10A101, contained on PWB EL10A121 and chassis mounted components designated as Assembly EL10A100. Component designators in the range of 101 to 199 belong to Assembly xxxxx101 (the PWB) and designators in the 1 to 99 range are chassis mounted.

Basic Load Function. Q1 through Q5 and associated emitter ballast resistors are the basic electronic load and are connected with low impedance conductors to the front panel “Load Input” terminals. In this path is R9, a 0.01 Ohm - 60 Watt TO-220 precision thick-film resistor, that is mounted to the heat sink extrusion. R9 provides the current sense for both internal and external monitoring.

Q1 is a voltage controlled device and requires no drive current from the control circuit, U102A and associated components. Q1 drives Q2 through Q5 from the power source under test (UUT) thus establishing the low Voltage performance of the EL-10A-1. As can be seen from the schematic, at full load the ballast drop plus V_{BE} of Q2 through Q5 requires approximately 3 VDC and although the EL-10A-1 is stable below 3 VDC (unlike some electronic loads) it does have limited performance as described in “Characteristics”.

The EL-10A-1 400 Watt and 40 ADC limits are determined by the current rating of R10 through R13 and the SOA rating of Q2 through Q5 . ***Use Caution to ensure the SOA rating is not exceeded.***

The basic constant current operation of the EL-10A-1 is quite simple. A stable reference voltage is supplied to the non-inverting input of U102A while R9 supplies a voltage to its’ inverting input. The high gain of U102A controls Q1, and in turn Q2 through Q5, holding the voltage across R9 at the same value as the reference voltage. Thus a fixed voltage across a fixed resistance produces a constant current that does not vary with the UUT’s voltage level. R112, R114 and C115 compensate U102A for stable operation into Q1’s high input capacitance.

Current Setting and Adjustment. The reference voltage for U102A originates with U101, a precision +2.5 VDC reference that is carefully connected to R9 to avoid stray currents influencing its’ output. The +2.5 VDC output is connected to R2 and R3, the “Low Current” and “High Current” 10 turn precision potentiometers. The two identical circuits provide 0 to 400 mVDC levels to the analog switch U104.

The “Load Step” switch selects which of U104’s inputs will be applied to the “Load Current Range” switch, S8. S8 and associ-

Theory of Operation: (continued)

ated, frequency compensated resistive, divider provides range selection of 1, 2, 4, 10, 20 or 40 ADC by appropriately scaling U104's output. The output of S8 is connected to the "Load" switch, S6 as the current mode input. S6B specifically, determines U102A's input by selecting S8's output, the "Resistive Load Range" switch output or the control circuit ground (common) which is isolated from the power line ground and chassis. R110, Load Current Zero, is adjusted at initial calibration for 0 load current with S6 in the Off position.

Load Current Step. As described above, the load current is set and selected by front panel controls and the choice of High or Low current is made with ""Load Current Step" switch, S10. This three position switch selects low or high current manually or "Auto". In "Auto", switching between high and low current is controlled by an external input, "Load Step Input". This 50 Ohm input requires a 0 to +5V pulse with < 1 µS rise and fall times. Practical pulse widths are 50 µS to DC as U103 is a DC coupled optical isolator, allowing the use of grounded pulse generators.

External Modulation. As discussed in "Characteristics" an input for external modulation allows more extensive evaluation of the UUT. The "Ext. Modulation" input is a 600 Ohm linear port that is transformer coupled into the reference voltage. As opposed to the step input this port is not DC coupled, but is linear so that frequency response testing can be performed on the UUT. The input should be -60 to 0 dB (referenced to 1 mW into 600 Ohms) over 10 Hz to 100 kHz. The actual level is set by observing the "Current Monitor Out" on an oscilloscope and setting the modulating voltage for the desired peak to peak current. T101 provides the transformer coupling into the output path of U104 and S11 provides a convenient means to turn the modulation on and off.

Resistive Load. A resistance capable of up to 400 Watts is simulated by applying a fraction of the UUT voltage to U102A as its' reference voltage. "Resistive Load Range", S4 provides switch-able scaling and "Resistive Load Resistance", R1 provides fine resolution setting. The effective load resistance is the ratio of (R1+ R24+R25)/R25 times R9. These values are chosen to provide 100:1 adjustment of resistance for each range and to produce 1 mV to 100 mV when fed with a 5 µA current from constant current source Q101. When S6 is Off and S5 is in "Ohms", this 1 to 100 mV voltage is applied to the voltmeter and displays the effective load resistance in Ohms. The decimal point is changed by S4 to properly display values for all three resistance ranges.

Voltage Monitoring. DPM, U1 is a 3 ½ digit LCD, 200 mV panel meter. In the prototype I used an inexpensive, consumer grade, generic import. While I have had good success with these low grade DPMs I have not been able to obtain sufficient specifications to recommend their use in any application other than prototyping or hobby applications. Even the distributors I contacted are unable or unwilling to even disclose the manufacturer. However, muRataPs, distributed by Mouser appears to have a reasonable priced 3 ½ digit LCD with complete specifications and warranty information.

The Voltmeter input, as selected by "Voltmeter Input" switch, S5 can either be from the Load Input terminals ("Internal") or from J6 and J7 ("External"). While "Internal" provides functional measurements, it provides readings degraded by the lead loss from the Load to the UUT. For performance measurements the "External" input should be used with test leads connected directly to the UUT's output terminals.

The "Volt-Ohm Range" switch uses 0.1% resistors to scale the DPMs 200 mV input to 2V, 20V and 200V with the Ohms position used as described in the Resistive mode. Allowance for input over-voltage protection is provided for with R126, R127, D103 and D104. The uncertainty here lies with the generic import DPM since insufficient information is available to determine if the unit has internal protection. A slight (approximately 0.2%) non-linearity is added when D103 and D104 are used, so I opted to test my DPM without diodes. It survived over-voltage with just R126 and R127; therefore, for the sake of accuracy, I deleted them in the prototype. As stated previously ***I can only recommend these generic DPMs for non-critical applications.***

Current Monitoring. A second DPM, U2, is used to monitor the load current. U102B is adjusted, using R103, for a gain of 10 and zeroed with R108 to provide 4.000 VDC output with 40.00 ADC load current. The "Amp Mtr" switch and associated 0.1% resistors scale U102B's output for 2, 20 and 200 ADC ranges. ***Note the maximum current is 40 ADC even on the 200 ADC range.***

S7, "Amp Meter" switch displays the set point current on the Amp Meter prior to actually turning the load on when in the "Set Load" position. Once the desired set point is obtained S7 should be switched to the "Load Only" position so that the Amp Meter will display the actual load current. If left in the "Set Load" position, the Amp Meter will over-range when the load is turned on. This switching can be made automatic, but it requires a custom switch for S6 that has a make-before-break "B" section and a break-before-make "A" section.

The "Current Monitor Out", J3, is a ground isolated 50Ω BNC monitor that provides 5 mV/A when terminated into 50Ω. ***J3 must be connected only to ground isolated test equipment.*** J3's shell is connected to the "Load Input Neg" terminal. This direct connection allows accurate transient measurements from DC to 10 MHz. Alternatively, the UUT can be ground isolated in order to use grounded test equipment. ***Failure to heed this requirement may result in erroneous current readings, instability or possible short circuiting of the UUT output.***

Caution: use an agency approved isolation transformer to safely ground isolate test equipment, which is required for both safety and proper operation of the EL-10A-1.

Applications:

Basic Power Supply Evaluation. The EL-10A-1 Electronic Load has many applications, including uses that are not obvious. However, Fig. 4 represents one of the most common uses, which is basic power supply evaluation. Sufficient detail is included to enhance understandability, however their is no substitute for hands-on experience testing power sources.

Basic Set Up. For the most part the interconnections shown in Fig. 4 are self-explanatory, but a few items need elaboration. First, the EL-10A-1 chassis is connected to the power line ground as are the pulse and signal generator input BNC connectors. However, the current monitor output BNC is isolated from power line ground, as are the control and monitoring circuitry. The oscilloscope used to monitor the current output must also be isolated from power line ground. ***Use caution and an agency listed isolation transformer to do this safely. Just removing the power line ground from the scope WILL NOT WORK as the ac leakage current will disrupt the EL-10A-1 control circuit and present a ac leakage current hazard.***

level and again at the high current level as set by the front panel controls. Well designed power supplies will have very little change in output voltage and may require the use of the "Poteniometric Voltage" feature. If required, adjust the poteniometric voltage to within -200 mV of the power supply's output, with no load, and set the DVM to the 200 mV range. Read the no-load (or low current) voltage and record, then switch to the higher current and again read and record the output voltage. The difference in readings represents the voltage change and if divided by the no-load (or low current) voltage and multiplied by 100 will yield load regulation in %.

Note, the no-load (or low current) and high current must be within the normal operating ranges of the UUT. Most linear power supplies have no minimum current requirement, but SMPS (switch mode power supply) sometimes do. Testing above the maximum output current will be discussed in a following topic on current limiting.

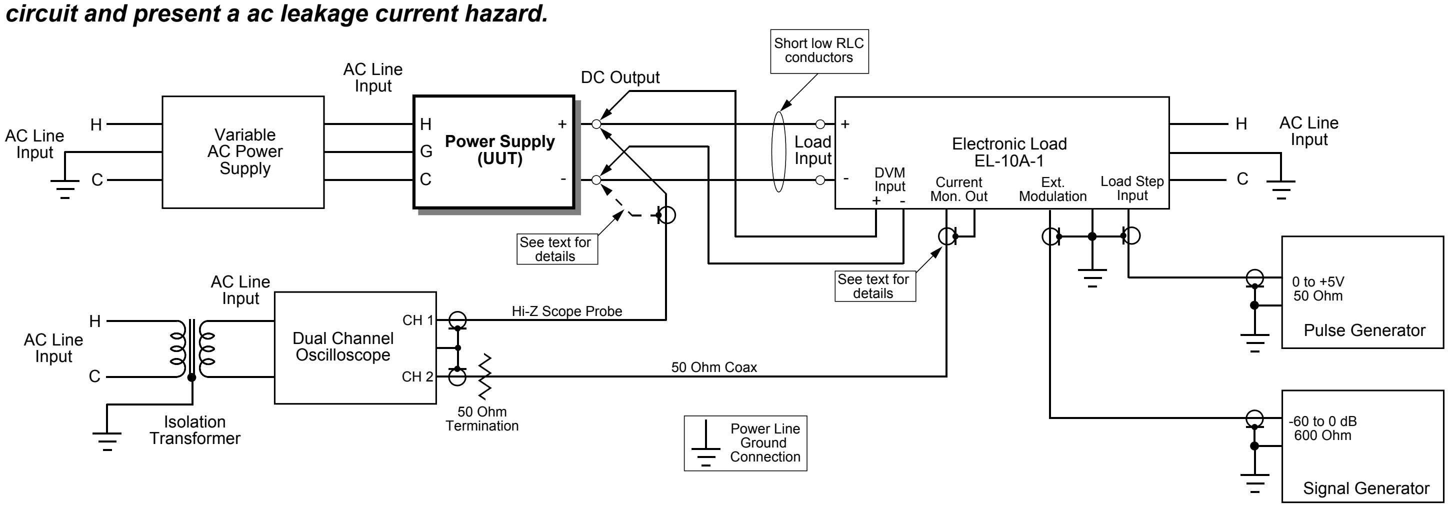


Fig. 4. Basic AC Line operated power supply test set up.

Also note the details of the oscilloscope shield connections. Shown as a dashed line, the CH 1 scope probe shield is connected to the UUT negative output. This connection is **not** used while observing the EL-10A-1 current monitor BNC. Once the current is set, remove the current monitor BNC and connect the scope probe ground of CH1 to the UUT negative output. This detail is important because the two points in question are separated by the resistance (and inductance) of the negative UUT to Load wire. While measuring transient performance, the contribution of the wire to the UUT output voltage is very significant and will produce erroneous readings if the above steps are not done properly.

Load Regulation. Probably the most common test performed on a power supply is load regulation, defined as output voltage change caused by load current change.

The set up in Fig. 4 is an easy way to evaluate this characteristic of the UUT. Simply read the output voltage at the low current

Also note, load regulation performance may vary with the incoming AC line voltage, so be sure it is adjusted to the correct value for evaluating the load regulation performance.

Line Regulation. Speaking of which, line regulation is probably the next most common test and closely related to load regulation. While complete characterization requires testing load regulation over the entire input voltage range (at several points), the basic line regulation can be determined by checking regulation at low and high input voltages for no-load (or low current) and high current outputs.

Note, in some cases load and line regulation specifications are lumped into a single "regulation" specification. Also note, other environmental and operating conditions may have unique specifications, for example stability over a specified temperature range, humidity, elevation or shock. Any of these can be tested with the basic configuration shown in Fig. 4 by exposing the UUT to the appropriate condition.

Applications: (continued)

Ripple and Noise. Ripple and noise are measured during the load and line test as well. Ripple is considered to consist of the incoming AC power line frequency and harmonics thereof. This can be measured on an oscilloscope using visual filtering to remove non-harmonic noise. Commonly the ripple is expressed as a peak-peak value or as a percentage of the output voltage.

Non-harmonic noise can be measured on an RMS voltmeter (with appropriate low pass filter to reduce the ripple contribution) or estimated from the oscilloscope ripple measurement. Sometimes the total ripple and noise is measured using a true RMS meter and so specified without differentiation of cause. The actual application will determine the effort necessary to adequately evaluate this performance. Well designed linear power supplies normally have ripple and noise levels that are insignificant thus requiring little effort to evaluate.

SMPS on the other hand, while much improved these days, are more likely to need careful evaluation of not only ripple (switching frequency and its' harmonics) and noise, but also a unique artifact. SMPS, due to their high frequency switching, generate high frequency energy that often appears at the output as spikes. While good design and construction practices minimizes this undesirable energy, it is certainly ever present in SMPS.

Step or Transient Response. Regulated power supplies, both linear and SMPS, use a feedback loop to control voltage and current. Ensuring loop stability and acceptable performance is a key element in power supply design. Complicating the stability issue is the unpredictable nature of loads a power supply may encounter. In a poorly designed or malfunctioning power supply the simple fact of changing the load current can sometimes cause instability.

The set up in Fig. 4 can be used for this purpose. This is the reason short, low RCL (resistance, capacitance and inductance) leads are required connecting the UUT and Load. It is extremely important to evaluate and understand the contribution the leads have on step performance. Typical modern power supplies have quite low output impedances, so low as a matter of fact that interconnecting lead impedance may exceed it.

Done carefully, step response reveals a lot about the control loop stability. Basically the load current is quickly changed from one level to another, e.g. from 0 to half load, while monitoring the UUT output voltage.

Fig. 5 is an example where the load current steps from 0 to 6A with a resultant output voltage change of ± 250 mV. The quickly damped ringing is indicative of a stable power supply. The larger the voltage spike and the greater the ringing, the less stable the UUT. It is instructive to add various value capacitors across the output terminals during this test. The actual loads the power supply may see are usually unknown, therefore the more conditions that can be simulated the better the power supply will be characterized.

External Modulation. A closer evaluation can be made of the control loop using the external modulation input to modulate the load current. With the external generator set for a level that

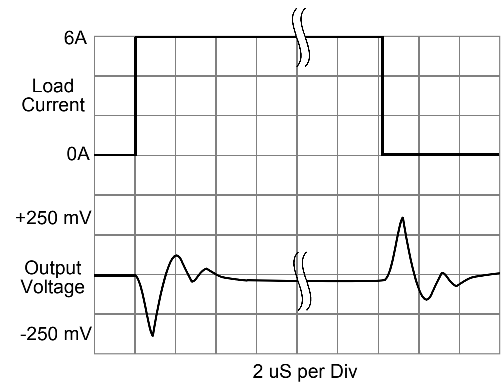


Fig. 5. Step response voltages and currents.

produces a peak to peak current that is within the 25 to 50% current capability of the UUT, the output voltage is measured. As the generator frequency is swept from 10 Hz to 100 kHz the output voltage is monitored for any unusual behavior. At the low frequency end, the control loop is the major contributor. As the frequency is increased, the control loop becomes less significant until the power supply's output filter capacitors predominate.

The output impedance of the power supply is the above observed peak to peak voltage divided by the peak to peak load current.

Current Limiting Characteristics. Most modern power supplies have a well behaved current limiting function; however, use caution when testing any power supply that you are not sure of. While voltage/current graphs are presented in various ways, I find the plots of Fig. 6 and Fig. 7 the easiest to understand.

Straight Line Current Limiting. Fig. 6 shows the voltage and current outputs of a 12 VDC power supply that has a 10 ADC straight-line current limit, also known as constant current limiting.

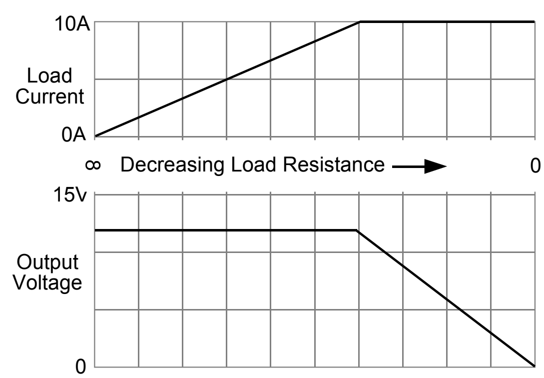


Fig. 6. Straight-line current limiting. Voltage and current vs Load Resistance.

Applications: (continued)

The output voltage is 12V for any load resistance up to an output current of 10A and then it decrease in direct proportion to the load resistance. That is pretty easy to understand because the current becomes constant at 10A, so by Ohms law, the output voltage is equal to 10A times the load resistance.

Fold-Back Current Limiting. Fig. 7 shows the voltage and current outputs of the same 12 VDC power supply except with fold-back current limiting that starts at 10 ADC. Again the output voltage is 12V for any load resistance up to an output current of 10A. Similar to straight-line limiting, the output voltage will decrease as the load resistance decreases; however, unlike straight-line limiting, the output current will also decrease from this point until it reaches the minimum fold-back current where it will remain. In this example that value is 5A.

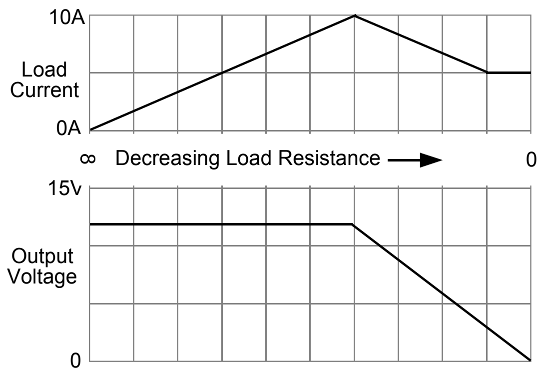


Fig. 7. Fold-back current limiting. Voltage and current vs Load Resistance.

In order to return to non-current limited operation, the load resistance will have to increase to a value equal to, or greater than the its' value when current limiting began.

Current Limiting Evaluation. The EL-10A-1 can be used to evaluate a power supply's current limiting characteristics in either the constant current mode or the resistance mode. Using the EL-10A-1 as a resistive load will produce the above graphs. I prefer this resistive mode evaluation.

Using the current mode will cause the output voltage to drop sharply as the current limit is reached. To exit this current limited state will require reducing the Load Current conductance to a compliance below the fold-back current limit. Kind of a bang-bang method for evaluation current limit performance.

Fold-back current limiting may have more quirks than straight-line limiting, but either method needs careful evaluation. Most control circuits have internal switching of the control function when current limit is encountered. This hand-off from voltage to current control can cause the power supply to become unstable.

More Extensive Evaluation. While beyond the scope of this application, I will note there are more extensive evaluations that may be appropriate based on the power supply's end use.

Some examples are;

- Power-on and off with full load.
  This condition can cause difficulty for some designs and may need evaluation.

- Reverse current
  Power supplies used to charge a stand-by battery should draw very little reverse current when the incoming AC line voltage is off. This is evaluated by simply applying the appropriate voltage to the power supply's output terminal with the AC power off. Typically designs that depend on a bleeder resistor for stability, will draw significant current in this application.

- Over-voltage protection
  While testing reverse current, it may be possible to test over-voltage protection. If the UUT uses a simply crowbar, then the reverse current test will yield OV limit by increasing the, ***current limited***, test voltage until the trip point is reached.

DC to DC power supplies have other characteristics that need evaluation, such as ripple rejection, kick-back, source impedance, RFI-EMI radiation and magnetostrictive noise.

EL-10A-1 400 Watt Electronic Load

Calibration and Alignment:

Step	Adjustment Calibration	Conditions	Adjust	Results
1	Initial warm-up	Allow 30 minutes warm up with the EL-10A-1 “AC Power” on, but no load or external inputs connected. The Voltmeter should automatically zero and the Amp Meter should be close to zero but will probably require adjustment after the warm up period. Refer to Fig. 8 and 10 to locate the adjustments for calibration and alignment, all are located on Assy EL10A101.		
2	Amp Mtr Zero	S9 “Amp Meter” to “2A” position S6 “Load” to “OFF” S7 ”Amp Meter” to “Load Only”	R108	±0.000
3	Load Curr Zero	S6 “Load” to “OFF” S7 ”Amp Meter” to “Load Only” S9 “Amp Meter” to “2A” position Apply 40 VDC to the “Load Input” Adjust R110 CW until a few milliamps register on the Amp Meter. Adjust R110 CCW very slowly until the current just goes to 0. Note R108 and R110 are 15 turn pots.	R110	+0.000
4	Amp Meter 2A Calibration	S6 “Load” to “Current” S7 ”Amp Meter” to “Load Only” S8 “Load Current Range” to “2A” S9 “Amp Meter” to “2A” position S10 “Current Step” to “High” R2 “High Current” full CW Apply 1.900 ADC to the “Load Input” using Lab Cal equipment or an accurate Amp meter	R103	1.900
5	Amp Meter 200A Calibra-tion	S6 “Load” to “Current” S7 ”Amp Meter” to “Load Only” S8 “Load Current Range” to “40A” S9 “Amp Meter” to “200A” position S10 “Current Step” to “High” R2 “High Current” full CW Apply 39.0 ADC to the “Load Input” using Lab Cal equipment or an accurate Amp meter ***Ensure compliance voltage does not exceed 10 VDC.***	R102	39.0
6	Volt Meter 200mV Calibration	S3 “Poteniometric Voltage” to “OFF” S5 “Volt-Ohm Range” to “200mV” S12 “Volt Meter” to “External” Connect an accurate 190.0 mVDC to “External Voltmeter Input”	U1 on board Cal	190.0
7	Volt Meter 200V Calibration	S3 “Poteniometric Voltage” to “OFF” S5 “Volt-Ohm Range” to “200V” S12 “Volt Meter” to “External” Connect an accurate 190.0 VDC to “External Voltmeter Input”	R125	190.0
8	Ohms Calibration	S3 “Poteniometric Voltage” to “OFF” S4 “Resistive Load Range” to “0.1 - 10 Ohms” S5 “Volt-Ohm Range” to “20V” S6 “Load” to “Resistive” S9 “Amp Mtr Range” to “”2A” S12 “Volt Meter” to “Internal” R1 “Resistance” fully CW 1. Apply approximately 9 VDC to “Load Input” and adjust R1 CCW for 0.900ADC while adjusting the external voltage source for 9.00 VDC on the EL-10A-1 Volt Meter 2. Reset the following switches S5 “Volt-Ohm Range” to “Ohms” S6 “Load” to “OFF”	R129	10.00

Component Locator for PWB:

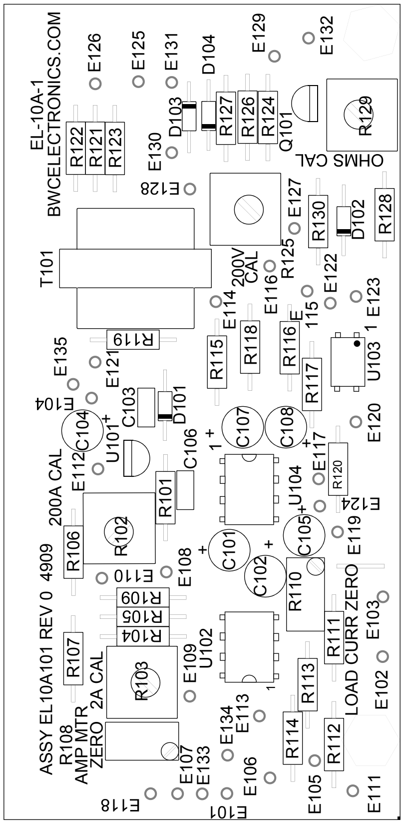


Fig. 8. Monitor and Control Assy EL10A101 component locator.

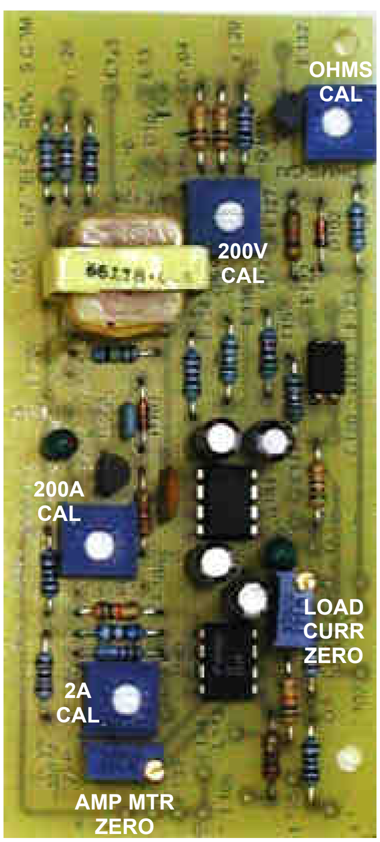


Fig. 10. Monitor and Control Assy EL10A101 top view.

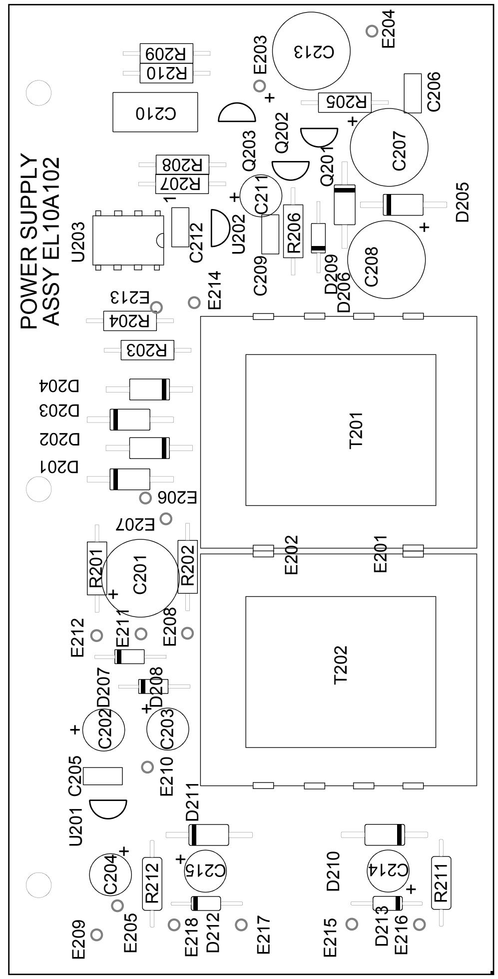


Fig. 9. Power Supply and Poteniometric Voltage Source Assy EL10A102 component locator.

Fig. 11. Power Supply and Poteniometric Voltage Source Assy EL10A102 top view.

Fig. 12. Top chassis view. Heat sink mounted transistors are at top along with thermal switch. Power supply is vertically mounted to heat sink and Control Board is chassis mounted. Note extensive components and wiring associated with the front panel controls.

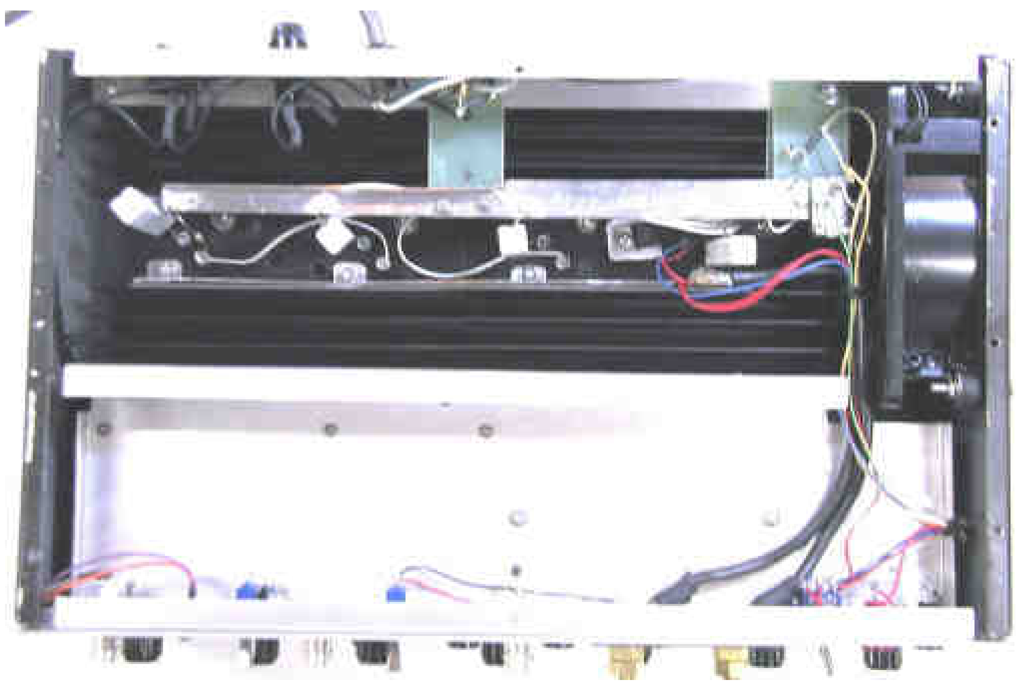
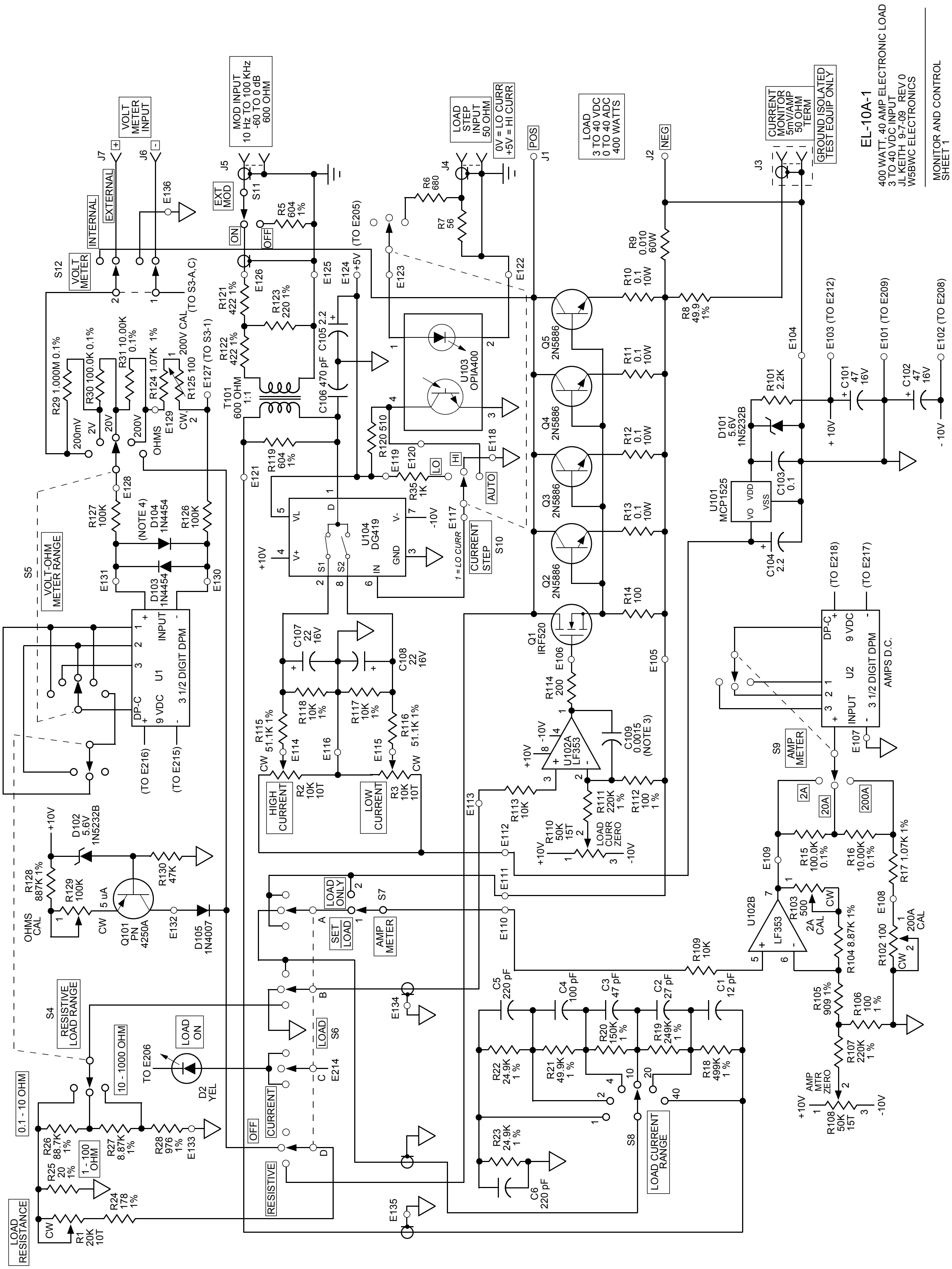
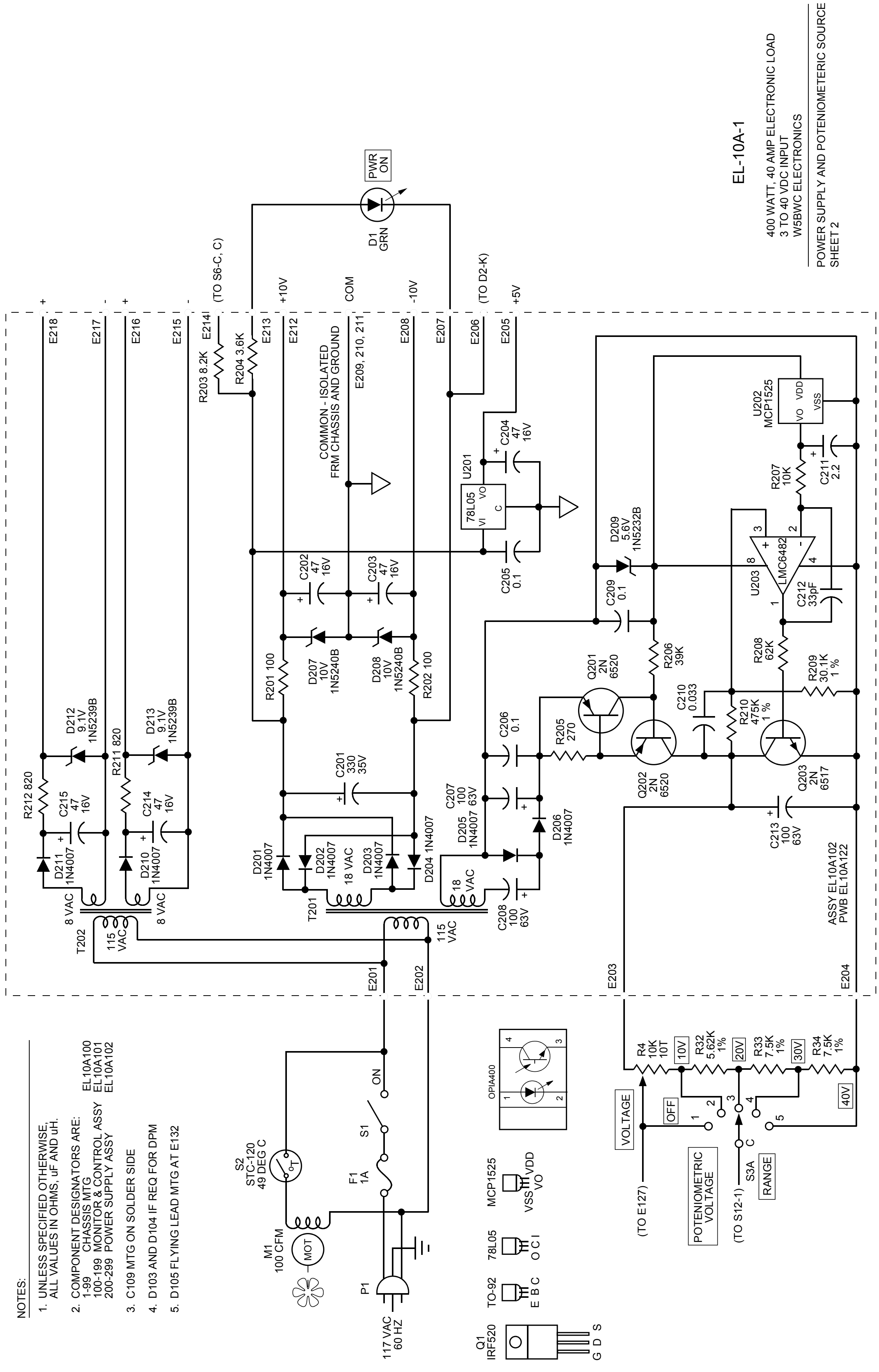


Fig. 13. Bottom chassis view. Bottom side of heat sink reveals ballast resistors and copper bus bars for the collector and emitter wiring. Note chassis primary purpose is to support the heat sink extrusion.

EL-10A-1 400 Watt Electronic Load



EL-10A-1 400 Watt Electronic Load



EL-10A-1 400 Watt Electronic Load

Material List - EL10A100 Chassis Assembly

Qty	Designator	Value/Type	Description	Part Number*	Supplier**
1	C1	12 pF	NPO ceramic disk	140-50N5-120J-RC	
1	C2	27 pF	NPO ceramic disk	140-50N5-270J-RC	
1	C3	47 pF	NPO ceramic disk	140-50N5-470J-RC	
1	C4	100 pF	NPO ceramic disk	140-50N5-101J-RC	
2	C5, C6	220 pF	NPO ceramic disk	140-50N5-221J-RC	
1	D1	T-1 ¼	Green LED	604-WP7113SGD	Mouser
1	D2	T-1 ¼	Yellow LED	604-WP7113SYD	
1	F1	250 VAC, 1A Fuse	5 mm x 20 mm Fast Acting	504-GMA-1	
2	J1, J2	0.25 x 20 Brass screws	with mtg Hdw	Shop Built	
3	J3, J4, J5	50 Ohm	BNC Bulk Head	161-9323	
1	J6	Banana Jack	Black	530-108-0903-1	
1	J7	Banana Jack	Red	530-108-0902-1	
1	M1	100 CFM 119mm Sq x 38mm	115 VAC	433-4E-115S	
1	P1	SJT Per Cord	18 AWG, NEMA 5-15P	173-53101-E	
1	Q1	IRF520	Power FET	512-IRF520A	
4	Q2,Q3,Q4,Q5	2N5886	25A, 80V, 200W	863-2N5886G	
1	R1	20k Variable	10 Turn, panel mtg	882-MW22B-10-20K	
3	R2, R3, R4	10k Variable	10 Turn, panel mtg	882-MW22B-10-10K	
1	R5	604 Ω, 1%	0.25 W MF	271-604-RC	
1	R6	680 Ω, 5%	0.25 W, CF	291-680-RC	
1	R7	56 Ω, 5%	0.25 W, CF	291-56-RC	
1	R8	49.9 Ω, 1%	0.25 W MF	271-49.9-RC	
1	R9	0.010 Ω, 2%	60W, TO-220	684-MP2060-0.01	
4	R10, R11, R12, R13	0.10 Ω, 5%	10 W Cement	280-CR10-0.1-RC	
1	R14	100 Ω, 5%	0.25 W, CF	291-100-RC	
2	R15, R30	100.0 kΩ, 0.1%	0.125 W MF	71-PTF56100K00BYBF	
2	R16, R31	10.00 kΩ, 0.1%	0.125 W MF	71-PTF5610K000BYBF	
1	R17	1.07 kΩ, 1%	0.25 W MF	271-1.07K-RC	
1	R18	499 kΩ, 1%	0.25 W MF	271-499-RC	
1	R19	249 kΩ, 1%	0.25 W MF	271-249K-RC	
1	R20	150 kΩ, 1%	0.25 W MF	271-150K-RC	
1	R21	49.9 kΩ, 1%	0.25 W MF	271-49.9K-RC	
2	R22, R23	24.9 kΩ, 1%	0.25 W MF	271-24.9K-RC	
1	R24	178 Ω, 1%	0.25 W MF	271-178-RC	
1	R25	20 Ω, 1%	0.25 W MF	271-20-RC	
1	R26	88.7 kΩ, 1%	0.25 W MF	271-88.7K-RC	
1	R27	8.87 kΩ, 1%	0.25 W MF	271-8.87K-RC	
1	R28	976 Ω, 1%	0.25 W MF	271-976-RC	
1	R29	1.000 MΩ, 0.1%	0.25 W MF	71-PTF651M0000BYBF	
1	R32	5.62 kΩ, 1%	0.25 W MF	271-5.62K-RC	
2	R33, 34	7.5 kΩ, 1%	0.25 W MF	271-7.5K-RC	
1	R35	1K Ω, 5%	0.25 W, CF	291-1K-RC	
1	S1	SPST Rocker Switch	250VAC, 6A	642-FMC12A220	
1	S2	N.O. 49 ^{O}C Thermal Sw	Chassis mtg	802-STC-120	
2	S3, S5	2 Pole, 5 Pos, Rotary	Non-shorting	105-SR2511F-25NS	
4	S4, S6, S9, S10	4 Pole, 3 Pos, Rotary	Shorting	105-SR2511F-43S	
2	S7, S11	SPDT, Toggle	Flat blade, panel mtg	1055-TA2130-EVX	
1	S8	2 Pole, 6 Pos, Rotary	Non-shorting	105-SR2511F-26RN	
1	S12	DPDT, Toggle	Flat blade, panel mtg	1055-TA2160-EVX	
2	U1, U2	3 ½ 200 mV DPM	LCD Panel mtg	PM-128 (6929ME)	MPJ
2	XD101, 102	T-1 ¼ LED	Panel mtg Ring & clip		
1	XF1	Mini-Fuse holder	5 mm x 20 mm panel mtg	441-R3-12-GRX	
1	XJ3	BNC Flat & Shoulder	Fiber washer kit		
11		Knobs	0.25" Rd Shaft	506-PKA50B1/4	
4		Feet	0.375" Recessed Bumper	534-721	
1		Heat sink Thermaloy 16073	11.00" extrusion	16073 X 11.00"	Thermaloy

* Items without a listing are from shop stock or shop built.
** Supplier is Mouser Electronics unless otherwise noted. MPJ is Marlin P. Jones

Material List - EL10A101 Monitor & Control Assembly

Qty	Designator	Value/Type	Description	Part Number*	Supplier**
1	C101, 102	47 µF, 16 V	Radial Al Electrolytic	647-UVR1C470MDD1TD	
1	C103	0.1 µF, 50 V	Ceramic	581-SR211C104KAR	
2	C104, 105	2.2 µF, 50 V	Radial Al Electrolytic	647-UVR1H2R2MDD	
1	C106	470 pF SL, 50 V	Ceramic	140-50S5-471J-RC	
2	C107, 108	22 µF, 16 V	Radial Al Electrolytic	647-UVR1C220MDD	
1	C109	1500 pF	Ceramic	140-50P2-152K-RC	
2	D101, 102	1N5232B	5.6 V, 0.25 mW Zener	512-1N5232B	
2	D103, 104	1N4454	Si switching diode	512-1N4454	
1	D105	1N4007	1A, 1 KV Rect	512-1N4007	
1	Q101	PN4250A	PNP Hi-gain small signal	512-PN4250A	
1	R101	2.2 kΩ, 5%	0.25 W, CF	291-2.2K-RC	
2	R102, 125	100 Ω Trimmer	0.375” Sq	652-3386F-1-101LF	
1	R103	500 Ω Trimmer	0.375” Sq	652-3386F-1-501LF	
1	R104	8.87 kΩ, 1%	0.25 W MF	271-8.87K-RC	
1	R105	909 Ω, 1%	0.25 W MF	271-909-RC	
2	R106, 112	100 Ω, 1%	0.25 W MF	271-100-RC	
2	R107, 111	220 kΩ, 1%	0.25 W MF	271-220K-RC	
2	R108, 110	50 kΩ, 15T Trimmer	0.375” Sq	652-3296W-1-503LF	
2	R109, 113	10 kΩ, 5%	0.25 W, CF	291-10K-RC	
1	R114	200 Ω, 5%	0.25 W, CF	291-200-RC	
2	R115, 116	51.1 kΩ, 1%	0.25 W MF	271-51.1K-RC	
2	R117, 118	10.0 kΩ, 1%	0.25 W MF	271-10K-RC	
1	R119	604 Ω, 1%	0.25 W MF	271-604-RC	
1	R120	510 Ω, 5%	0.25 W, CF	291-510-RC	
2	R121, 122	422 Ω, 1%	0.25 W MF	271-422-RC	
1	R123	220 Ω, 1%	0.25 W MF	271-220-RC	
1	R124	1.07 kΩ, 1%	0.25 W MF	271-1.07K-RC	
2	R126, 127	100 kΩ, 5%	0.25 W, CF	291-100K-RC	
1	R128	887 kΩ, 1%	0.25 W MF	271-887K-RC	
1	R129	100 kΩ Trimmer	0.375” Sq	652-3386F-1-104LF	
1	R130	47 kΩ, 5%	0.25 W, CF	291-47K-RC	
1	T101	1:1 600 Ω	PWB Mtg Audio Xfmr	553-TY145P	
1	U101	MCP1525	Prec. 2.5 V Reference	579-MCP1525ITO	
1	U102	LF353	FET Op Amp	512-LF353N	
1	U103	OPIA400	Optical Isolator	828-OPIA400TU	
1	U104	DG419	Analog Switch	781-DG419DJ-E3	
1		PWB	Etched and drilled	EL10A121	Far Circuits

Note: D103 and D104 are optional depending on the over-voltage requirement of U1.

* Items without a listing are from shop stock or shop built.
** Supplier is Mouser Electronics unless otherwise noted.

Material List - EL10A102 Power Supply Assembly

Qty	Designator	Value/Type	Description	Part Number*	Supplier**
1	C201	330 µF, 35 V	Radial Al Electrolytic	647-UVR1V331MPD	
5	C202, 203, 204, 214, 215	47 µF, 16 V	Radial Al Electrolytic	647-UVR1C470MDD1TD	
3	C205, 206, 209	0.1 µF, 50 V	Ceramic	581-SR211C104KAR	
3	C207, 208, 213	100 µF, 63 V	Radial Al Electrolytic	647-UVR1J101MPD	
1	C210	0.033 µF, 100 V	Polyester	140-PF2A333K	
1	C211	2.2 µF, 50 V	Radial Al Electrolytic	647-UVR1H2R2MDD	
1	C212	33 pF, 50 V	NPO Ceramic	140-50N5-330J-RC	
8	D201-206, 210, 211	1N4007	1A, 1 KV Rect	512-1N4007	
2	D207, 208	1N5240B	10 V, 0.5 W Zener	512-1N5240B	
1	D209	1N5232B	5.6 V, 0.5 W Zener	512-1N5232B	
2	D212, 213	1N5239B	9.1 V, 0.50 W Zener	512-1N5239B	
2	Q201,202	2N6520	350 V, PNP	512-2N6520TA	
1	Q203	2N6517	350 V, NPN	512-2N6517BU	
2	R201, 202	100 Ω, 5%	0.25 W, CF	291-100-RC	
1	R203	8.2 kΩ, 5%	0.25 W, CF	291-8.2K-RC	
1	R204	3.6 kΩ, 5%	0.25 W, CF	291-3.6K-RC	
1	R205	270 Ω, 5%	0.25 W, CF	291-270-RC	
1	R206	39 kΩ, 5%	0.25 W, CF	291-39K-RC	
1	R207	10 kΩ, 5%	0.25 W, CF	291-10K-RC	
1	R208	62 kΩ, 5%	0.25 W, CF	291-62K-RC	
1	R209	30.1 kΩ, 1%	0.25 W MF	271-30.1K-RC	
1	R210	475 kΩ, 1%	0.25 W MF	271-475K-RC	
2	R211, R212	820 Ω, 5%	0.25 W, CF	291-820-RC	
1	R211, 212	820Ω, 5%	0.25 W, CF	291-820-RC	
1	T201	Dual 18 VAC @ 130 mA	115 VAC PWB mtg xfmr	838-3FS-336	
1	T202	Dual 8 VAC @ 140 mA	115 VAC PWB mtg xfmr	838-3FS-216	
1	U201	78L05	100 mA TO-92 Regulator	595-UA78L05ACLPME3	
1	U202	MCP1525	Prec. 2.5 V Reference	579-MCP1525ITO	
1	U203	LMC6482	Lo Volt Rail-Rail Op amp	LMC6482AIN-ND	Digi-Key
1		PWB	Drilled and etched	EL10A122	Far Circuits

* Items without a listing are from shop stock or shop built.
** Supplier is Mouser Electronics unless otherwise noted.

Prototype Test and Notes:

Notes:
After the completion of the final wire routing, it was discovered U102A required additional compensation to deal with Q1's input capacitance and wiring capacitance. C109 is mounted on the solder side of the EL10A121 PWB. If a future board revision is required, this capacitor will be added top-side.

S6 must have a make-before-brake (shorting) section for S6-B to prevent an open circuit at U102A's input during the switch transition. Without this the EL-10A-1 will produce a near short circuit momentarily to the Load terminals.

However, S6A must have a brake-before-make (non-shorting) function to prevent a momentary short between the output and input of the control circuit.

Also, S6D must have a brake-before-make (non-shorting) function to prevent a momentary short between the output and internal + 10 VDC through Q101 and D102. D105 was added to prevent this no matter what, since D207 is destroyed if this happens.

Bottom line is S6 needs to be a custom switch with one shorting section and three non-shorting sections. If not available, the connection from S7-2 to S6A must not be used. This changes the operation of S7 to where it reads the set point in the "SET/LOAD" position and the Load current in the "LOAD ONLY" position. If S6 is the proper switch and wired as shown S7 could read the set point and then the output current in the "SET/LOAD" position.

AC line leakage currents and ground loops always need attention, but especially so with the EL-10A-1. The low (5 mV/A) current monitor is particularly susceptive to this problem. A ***single point*** power line ground placed appropriately at one of the UUT output terminals will often help reduce the ac leakage artifact. Experience will help establish the best method of dealing with this nuisance that appears as power line ripple on the current monitor point. ***Do Not*** connect ungrounded equipment to the current monitor point without using an isolation transformer. If just the ground is removed from line operated equipment, the leakage current from the mains will be sufficient to disrupt the EL-10A-1 control circuits.

Prototype Test Results:

Constant Current Regulation						
Input Voltage	Load Current	Regulation (%)	Load Current	Regulation (%)	Load Current	Regulation (%)
40.0	10.00	Ref				
20.0	19.00	< 0.05				
10.00	19.00	< 0.05	30.0	Ref	40.0	Ref
3.20	19.00	< 0.05	30.0	< 0.05	39.95	-0.10
3.00	19.00	< 0.05	30.0	< 0.05		
2.07	19.00	< 0.05	29.96	-0.10		
2.00	18.98	-0.10				

Constant Resistance Regulation			
Resistance set for 0.10 Ohms			
No change above 3 VDC			
Input Voltage	Load Current	Effective Resistance	Error frm Ref (%)
3.05	29.61	0.103	Ref
2.02	19.70	0.103	0
1.54	15.14	0.102	-1.0
1.15	10.25	0.112	+12
1.00	7.13	0.140	+40
0.64	0.64	1.0	Stable

Transient Response:

12 Volt NiCd battery pack with 0.25" by 0.10" leads. Load step from 0 to 40 Amp with 5 mS pulse width and 10% duty cycle. No ringing or overshoot. 10% to 90% = 32 Amps in 4µS for 32A/µS or 8000 kAmps/Sec.

1.5 Volt D cell with direct negative terminal contact and 2" AWG 4 braid to positive terminal. As above except pulse amplitude of 8 Amps. 10% to 90% in 5 µS for 6.4A/µS or 1600 kAmps/Sec

Prototype Test and Notes: (Continued)

Prototype Test Results:

Thermal Tests (T_A = +25 °C Fan on unrestricted air flow)						
V_I	I_L	P_D	T_S	T_J	P_J	ΔT_{JS}
11.43 V	25.0 A	285.8 W	62.5 °C	130.0	62.51 W	67.5 °C
11.10	30.0	333.0	68.8	145.8	71.33	77.0
10.8	35.0	378	Rise too high too fast - aborted			
11.68	32.0	373.8	74.5	160.8	79.9	86.3
Testing at the limits of DC SOA on prototype reveals design calculations for 400 W continuous dissipation is marginal. Actual limit based on design objective T_J is 373.8 W at T_A = +25 °C or 26.2 W short of the stated dissipation.						

Based on the prototype testing I suggest anyone copying this design either increase the cooling capacity or be aware the prototype mechanical design did not quite meet the 400 W level. The SOA is fine at 400 W, so one option is to limit 400 W testing to 8 minutes on and 2 minutes off.