High Reliability Electronics for LIGO
R. Abbott
26 November, 2008

1. Overview

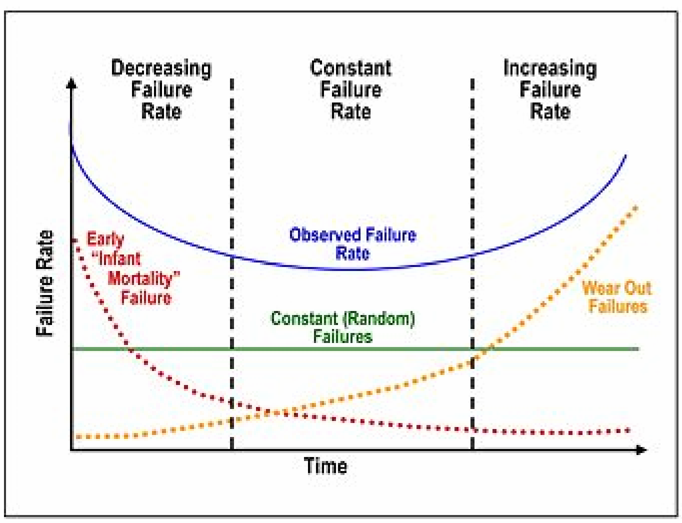
Advanced LIGO will see an increase in the use of electronic subassemblies within the vacuum system envelope. The inaccessibility of in-vacuum electronics, coupled with the high cost of repair, necessitates the use of more stringent electronics design practices. This note is intended to be a living document evolving as we become aware of additional areas that compromise reliability in electronics, or more effective countermeasures.

These techniques are intended for electronics used physically inside the vacuum system.

2. **Failure Modes**
   - 2.1. Summary of failure modes
     - 2.1.1. Infant Mortality
     - 2.1.2. Application of Reversed Polarity DC Power
     - 2.1.3. High Inrush Currents upon Application of DC Power
     - 2.1.4. Unbalanced DC Power Supplies
     - 2.1.5. Over Voltage Transients and noise on Input and Output Wires
     - 2.1.6. Component De-rating and
     - 2.1.7. Miscellaneous TopicsRELAYCONTACTScablecrosstalk

3. **Infant Mortality –** The well known "bathtub curve" describes the observed failure rate of components vs. time. As the name implies, it looks like a bathtub.

Figure 1 Bathtub Curve



3.1. **Mitigation** - Careful selection of quality components coupled with sensible usage will obviously lower the observed failure rate for a given scenario. Beyond this, it may be useful to institute a burn-in period for critical electronics so that the susceptibility to early infant mortality failure can be managed.

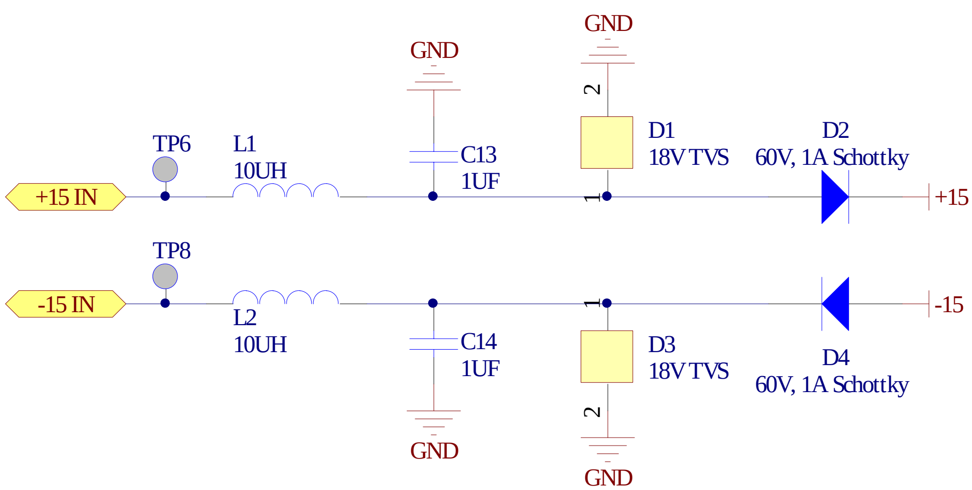
4. **Application of Reversed Polarity DC Power –** Certainly, anyone who's been with LIGO for any appreciable amount of time has seen their fair share of this sin. Even momentary application of reverse voltages to a circuit can cause permanent damage to active and passive components resulting in shortened lifespan or immediate failure.

4.1. **Mitigation** – Several design methods have been successfully employed to avoid reverse polarizing electronics

4.1.1. Adherence to "Standard LIGO Electrical Interfaces", T060123. This document establishes standards for connections between electronics used at LIGO. This addresses the more common scenarios encountered in the electrical connections between systems. I recommend this as the first line of defense.

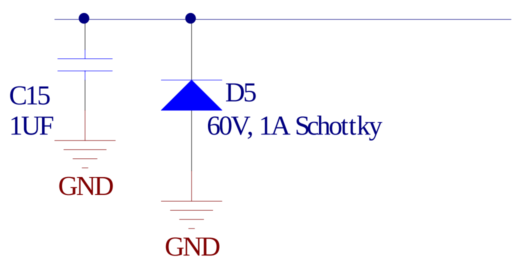
4.1.2. Diodes in series with the power feeds have been successfully used. The relatively large voltage drop across the diode renders this technique more useful in low power applications. Diodes D2 and D4 in figure 2 illustrate this technique. Schottky diodes are preferable due to the low voltage drop during forward biased operation.

Figure 2



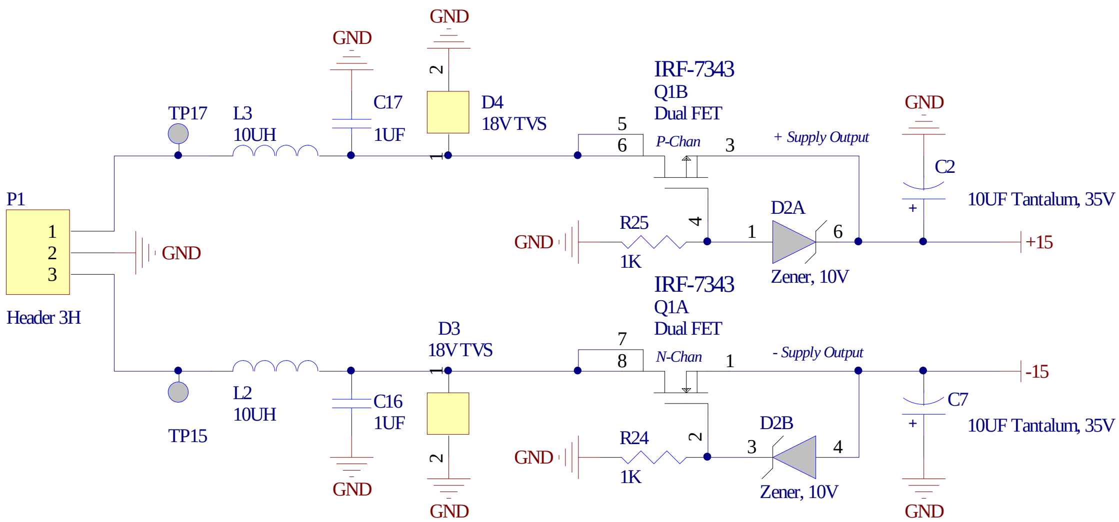
The parallel configuration, as shown in figure 3 should be avoided. Although the parallel configuration provides a clear indication that the DC power is connected backwards, it could result in failure of the relatively fine gauge wire used in the in-vacuum wiring harnesses. In any case where the in-vacuum wiring is threatened by high current, fuses or other positive means must be used to protect the in-vacuum wiring.

Figure 3, don't do this on power feeds



4.1.3. **MOSFET Reversed Polarity Protection –** For applications where the voltage drop across a Schottky diode is a problem, a complimentary pair of MOSFET transistors has been used. This circuit has less power dissipation, which can be useful for higher power in-vacuum electronics. Figure 4 shows a schematic using the commonly available IRF-7343 Dual MOSFET.

Figure 4



During operation, the MOSFET on-resistance is typically less than 0.1 ohms. L3 and L4 must be "lossy" ferrite based inductors with impedances of ~1 kohm or more at 100 MHz to avoid ringing.

5. **High In-rush Current upon Application of DC Power –** This category focuses on the damage to capacitors used to filter DC power supplies. It is fairly standard in industry to quote the use of a series current limiting resistor in series with a high quality, low equivalent series resistance (ESR) capacitor. The value of the resistor depends on the in-circuit voltage of the capacitor.

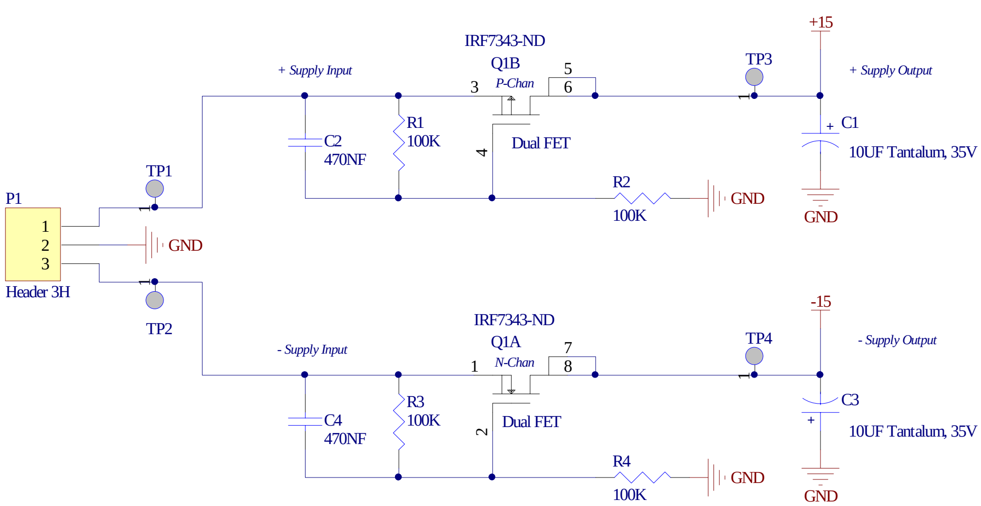
For example; a capacitor with a dielectric rating of 35 volts and an ESR of 0.05 milli-ohms is used to filter a 10 volt power line. At the instant the 10 volt supply is connected, the theoretical peak current is 10/0.05 amps, or 200 amps. In reality, nature is probably a bit more kind and things conspire to reduce that number, but the point is still clear. The high peak current can cause failure of the capacitor. Tantalum capacitors have a nice capacity to self-heal, but there are certainly thresholds that will result in an immediate and catastrophic failure. Unfortunately, tantalum capacitors almost never fail as an open circuit, but prefer the more spectacular short circuit scenario.

Hot-swapping is the act of connecting an electronic device to an energized power supply. This is not an uncommon practice in LIGO. I have personally measured the rise-time on a 10uF tantalum capacitor directly connected to a 15 volt supply, and the whole thing is over in less than 10usec. This raises the issue of how switches are used to energize circuitry.

It is conceivable that a designer could have a local power switch, which upon the instant of contact closure, could apply a rapid voltage step to a circuit. This, in turn provides the means to force excessive current through capacitors. Therefore, it is would be best to locate the switch upstream of a local power regulator board, and let the regulator take the hit, rather than jamming a pulse of destructive current into a sensitive circuit.

5.1. **Mitigation –** When power is applied to the circuit shown in figure 5, the MOSFETs turn on slowly, thus limiting the current into the tantalum capacitors. For +/- 15 volt applications, the turn on transient takes about 1msec.

Figure 5, Soft-start circuit.



6. **Unbalanced DC Power Supplies** – Some op-amps draw excessive current through parasitic internal diodes when only one of the two power rails is present ("rail" in this context, refers to one polarity or the other, of a bipolar power supply. Examples might be; +/-12 volts DC, +/-15 volts DC etc.). This leads to excessive heating and possible failure of the IC. Unfortunately, attempts to find amplifiers without this tendency have not been very successful. It is still common to find some applications that can only be properly served by these ill tempered devices.

Scenarios leading to unbalanced DC power supplies include: failure or deliberate removal of one power rail, blown fuses, wiring errors, board level component failure etc.

6.1. **Mitigation** – We have yet to utilize a board level solution suitable for inclusion into in-vacuum modules. Whenever possible, we use ganged switches and circuit breakers that simultaneously remove or apply both power rails. Figure 6 shows a commercial thermal circuit breaker that acts as an on/off switch as well as providing over-current protection. These devices are commonly used at the chassis level at LIGO.

Figure 6, Dual Circuit Breaker/ On-Off Switch

7. **Over-voltage on Input and Output Lines** – Sources of over-voltage include: Overshoot from under-damped power supplies and power distribution components, inadvertent application of higher than intended voltage, lightning or other sources of environmental transients, electrostatic discharge etc. These voltages are transmitted by the wiring serving a remotely located piece of equipment. Unfortunately, given the high current nature of typical power supplies at LIGO, there aren't any viable solutions to the simple application of the wrong voltage. For example, if a 15 volt supply was connected to a 5 volt load, a typical 15 volt LIGO power supply would likely destroy any zener based protection scheme quite rapidly.

7.1. **Mitigation –** Several means have been used to limit over-voltage transients

7.1.1. **Procedural –** Before applying power to a device, have in mind the anticipated current and voltage you expect to see. Carefully watch the power supply meters to verify the predicted response. Following this process will raise the probability that any zener protection device will survive the abuse.

7.1.2. **Resistive Isolation –** Whenever permissible by design, a series resistor is a cheap and predictable isolation between distribution wiring and a sensitive design.

7.1.3. **Transient Voltage Suppressors –** Figure 7 shows a surface mount transient voltage suppressor. These tiny devices are available in a wide variety of breakdown voltages, and can be of a unipolar or bipolar voltage breakdown nature. They are extremely fast (1psec) and are appropriate for use at their rated voltage. These devices have been successfully used in the ELIGO OMC.

Figure 7 Littelfuse® SMAJ Series, 400W Transient Voltage Suppressor

7.1.4. **Inductive Isolation and RFI Filters –** The use of a series inductor at the board level of an in-vacuum assembly must be approached with some care. A typical high quality RF inductor on a power feed will resonate with the de-coupling capacitors commonly found on a circuit board. The voltage ringing transient associated with this resonance can easily double the applied voltage in the presence of a sharp rise-time voltage step, not to mention causing a peak in the response of the filter. Care must be taken to use “lossy” ferrites or resistive damping to control the ringing, and each design should be bench tested with this in mind. Inductive isolation in conjunction with

8. **Component De-rating –** Operating electronic components well below their maximum ratings can have a significant impact on reliability. See the graphs in figures 8 and 9 to see how de-rating can effect the failure rate of tantalum capacitors.

Figure 8 Correction to failure probability vs. temperature

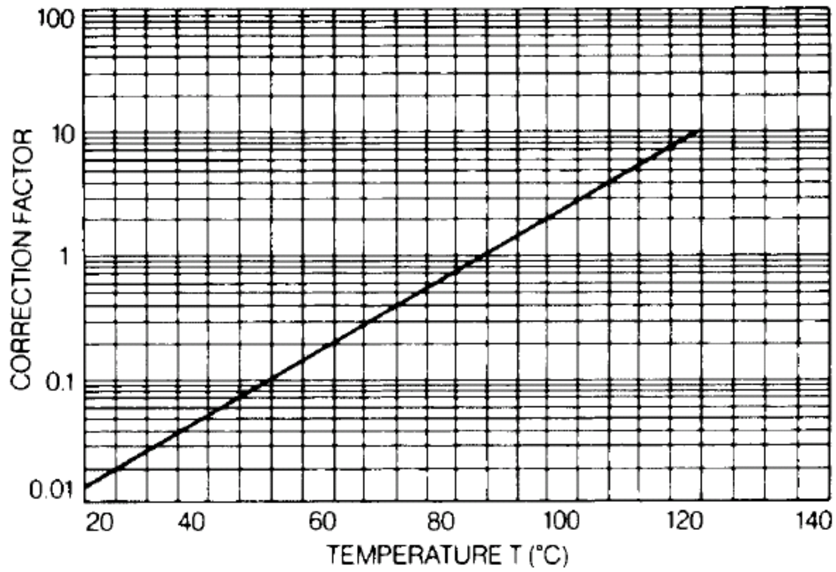
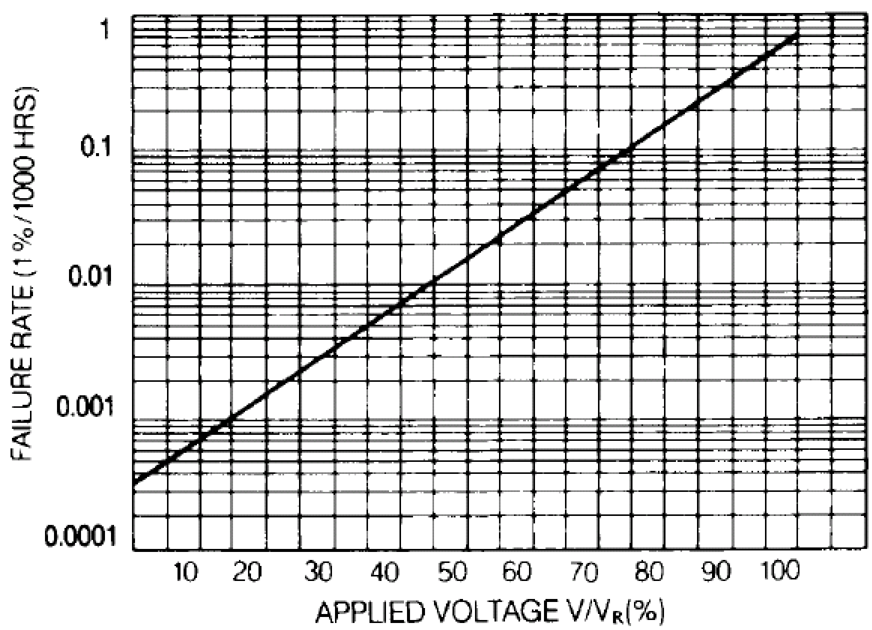


Figure 9 Correction to failure probability vs. voltage de-rating



It's easy to see how a relatively small change to a bill of materials can have a profound effect on reliability.

9. **Miscellaneous Topics –** As a collection point for random topics, the next section will likely expand over time
   9.1. **Connectors –** Cable connectors used within a sealed electronics pod should be minimized by design and eliminated wherever possible. Preference should be given to directly soldered wires. Mating contact surfaces should be gold plated.
   9.2. **Relays –** When relays are required in a high reliability design, it is sometimes possible to put contacts in parallel to create a type of built-in spare thus reducing the failure probability. The Omron G6H series of surface mount relays has been used with good results, and has a contact rating of 2 million cycles.
   9.3. **Cable Crosstalk –** It is important to evaluate the coupling of wires within bundles to preclude the possibility of design failure. This type of design flaw can require the same amount of misery as an actual component failure. As the wire-to-wire coupling increases, systems with gain first exhibit noise amplification, but then can actually form a local oscillation with neighboring systems.

   Unfortunately, these types of problems are not always visible during bench testing, so the systems must be evaluated in situ.