DESIGNING FOR EMP AND GUIDELINES FOR EMP HARDENING

ELECTROMAGNETIC PULSE (EMP)—INTRODUCTION

Damage to electronic equipment caused by EMP is manifested in two effects. The first effect is hardware damage, usually in the form of semiconductor burnout. The second effect is electronic upset, usually in the form of data transmission loss or the loss of stored data.

EMP couples into electronic equipment by three different paths. Deliberate antennas used for RF transmission is the first path. In general, antennas having a rejection bandwidth below 100 MHz will filter out damaging EMP energy. Any transient sensitive device, however, such as a microwave detector diode, which is directly in line from a deliberate antenna, should be suspected as vulnerable, regardless of operating frequency.

The second coupling path for EMP is through non-deliberate antennas. These antennas may be in the form of power lines, data transmission lines, mechanical shafts, or metallic coolant tubing. Any conductive appendage to an electronic device that is not electrically bypassed or decoupled in the EMP bandwidth prior to entry into the equipment item can constitute a non-deliberate antenna.

The third EMP coupling path is via direct penetration into the electronic device. Penetration may be either by diffusion of energy through non-effective shield walls or propagation of energy through apertures. Non-effective shield walls may consist of walls which are conductive, but too thin to stop low-frequency magnetic waves. They may also be walls that are low in conductivity, thereby constituting a transfer impedance to external surface currents. Apertures in equipment enclosures consist of any non-conductive openings or slits that will allow a reradiation or incident EMP energy within the enclosure.

Internal cables and electronic boxes located within reach of the effect of these EMP field penetrations will have currents induced on the cable shields and box surfaces similar to those induced on the exterior of the system. The cable shield currents will flow along the cables to ground and will capacitively or inductively couple to the inner conductors of the cables, producing signals at the box interface pins. In addition, box surface currents will penetrate the box in the same manner that the exterior field and system level surface currents penetrate the box, and affect sensitive electronics inside the box, depending on the penetration magnitude, box design, and part sensitivity. Also of concern to internal box circuits (buried circuits) is the method of mitigating the EMP-induced interface currents. If the interface currents are allowed to penetrate the box wall before being reduced, they may still reradiate to the interior, causing sensitive circuits to upset or burn out.

Table 1 gives a spectrum of the burnout and upset energies for some typical electronic parts. These are gross approximations and are only intended to illustrate that low-power, high-speed, narrow-junction, and low-saturation devices are more susceptible to EMP-induced burnout than the larger power devices.

Energy (joules)	Possible Damage
10^{-7}	Microwave mixer diodes burn out
10^{-6}	Linear IC's suffer upset and burn out
10^{-5}	Low power transistors and bipolar IC's upset and burn out
10^{-4}	CMOS logic, medium power transistor and diodes and capacitors suffer permanent damage
10^{-3}	Zeners, SCR, JFET's, high-power transistor and thin film resistors damaged

Table 1. Effects of EMP-induced Currents on Electronic Components

Designing against EMP is basically the same as designing against EMI/RFI or lightning and the same general rules apply. Some of the important aspects to be considered are those identified in Table 2.

SHIELDING
- Acceptably Thick Aluminum Walls
- All Joints Lapped and Gasketed
- Metal to Metal Is Preferred
- Cooling Ports Closed with Screen and/or Honeycomb Sections
- Penetrating Screws, Bolts, Shafts, etc., Grounded with Conductive Mating Surfaces

CABLE SHIELDS
- Shielding Effectiveness of Overall Shield
- Additional Shielding from
  - — Internal shields
  - — Cable layout
- Shield Continuity Required at Connectors

GROUNDING
- Equipotential — Acceptable for Localized Areas
- Floating Grounds — Best between LRU's

TRANSIENT SUPPRESSION
- Filtering
- Limiting

Table 2. Hardening Techniques against Effects of EMP-generated Currents.

Solid-shell enclosures of moderately thick aluminum can provide very high degrees of total shielding effectiveness. Cans, boxes, or other shielding enclosures take many forms. The ideal, continuously welded enclosure is almost never used because the equipment that it encloses then becomes inaccessible. The real shield is, in almost every case, degraded by the presence of penetration and various access doors. This gives rise to the necessity of considering the various techniques for maintaining shielding integrity in the presence of these unavoidable degradations.

The mechanical assembly of a shield must have clean metal-to-metal matching surfaces. Good contact between the surfaces should be assured by using either a continuous bond or set screws or rivets at close intervals. For maximum EMP shielding protection, special gasketing is used to ensure metallic contact at very short intervals. Any of several types of conductive gaskets may be used to close the opening, but it must be thick enough and soft enough to fill in all irregularities. Metal-to-metal matching surfaces are the best for EMI/EMP environment.

When openings are necessary for air flow, various forms of screens should be used to break the large openings into a series of small openings which act to reduce EMP field penetration through the openings. To be most effective, the intersections between openings must be fused. Three commonly used devices are honeycomb, perforated metal sheet, and wire mesh screen. Honeycomb is the most effective for large openings, and offers the additional advantage of low resistance to air flow. Wire mesh screen is useful in providing some shielding for vent holes that are too small to accommodate a honeycomb shield.

Openings which require visibility are often required for display devices, such as meters, display screens, lamps, etc. Large display apertures, such as are required for oscilloscope screens or plasma display panels, generally require special shielding. At times, it is necessary to use see-through wire mesh screen in front of the display panel in conjunction with a solid metal shield behind the panel or cathode ray tube. High-permeability metal shielding material is available for this application. The cathode ray tube is particularly difficult to shield, since it usually contains electrodes that extend for a considerable distance in front of the rear metal shielding material.

The use of overall shields on cable is mandatory when exposure to EMP is possible. Closure of apertures in package walls will be useless if transients are then allowed to flow freely on penetrating cables. The best cable shields are solid materials, such as rigid conduit or pipe. Such shields should be used where the weight and/or assembly penalty is not excessive. Where weight is a consideration, metal braid shields can be used effectively. As with package shields, the continuity of shields must be maintained at the back shells of interface connectors. In particular, the overall shield must have circumferentially complete termination of the connectors. Pigtail terminations do not provide acceptable continuity. The use of special EMI/RFI protective connector back shells is recommended where possible.

Cable circuits carrying sensitive digital or analog data may sometimes be replaced by fiber optic data links. These non-conductive fiber cables are immune to induced transients from EMP exposure.

Proper grounding schemes are important in helping to reduce system vulnerabilities to transient ground currents, and to maintain overall shielding integrity. At each level, the shielding and grounding topology portrays the shield as a barrier to its external environment, and the grounding as a means of controlling potential differences within a level. An important rule of effective shielding and grounding practice is that topological grounding conductors should never penetrate shield surfaces. This implies equipotential grounding for localized areas within a shielding area through a single ground termination. Floating grounds are acceptable and most useful between line replaceable units (LRU).

Where normal data transmission rates or bandwidths are very low, it may be appropriate to suppress transients by means of floating. This will allow the normal signals to pass through, while limiting the amount of noise energy which can enter the interface circuits.

If filtering alone is not sufficient to reduce the noise to safe levels, then the use of protective limiters is required. In particular, Zener diodes are useful for protecting solid-state components from excessive voltages. Zeners, though, have turn-on times on the order of a few nanoseconds, so some high-frequency filtering will be required to prevent energy from bypassing the Zener during its turn-on. Such filters can be in the form of connector feed-through filters or simple inductance-capacitance filters composed of shielding beads and small, high-frequency capacitors. Another device occasionally found useful is the spark gap for high current signals. Since a spark gap is inherently slow, it is usually paralleled with a Zener or Tranzorb to clip the leading edge of the current pulse until the spark gap triggers to shunt the Zener and prevent it from burning out.

GENERAL HARDENING GUIDELINES

The following guidelines are presented to provide the designer with basic solutions when a vulnerability to EMP has been isolated. Careful analysis of each possible EMP penetration, along with testing of the final design, are the ultimate requirements for assurance of EMP hardness without costly overdesign.

1. Metallic enclosures which could include composites for equipment should be employed. All seams should be electrically bonded. The dimensions of non-conductive openings should be minimized.
2. Electrically sealed chambers should be employed behind displays or other interfaces that require large openings in the equipment enclosure. EMP protection devices, which are subject to radiating high voltage or current transients should be placed in separate chambers bonded to exterior walls.
3. Close braid shields or continuous foil shields should be employed over interface wires that cannot be otherwise protected from EMP. All EMP shields should be terminated at the periphery of enclosures. Conductive back shells should be used on connections for shield termination.
4. Filter interface lines should be used that do not operate in the EMP spectrum. Filter designs should be selected that will not break down due to EMP transients.
5. Voltage or current parameters on interface lines that must operate in the EMP spectrum should be limited. Series or shunt resistors and Zener diodes or transient suppressors can be used.
6. Interface electronics should be isolated from sensitive internal circuitry such as microprocessors or random accessor memories. Internal enclosure ground loops should be prevented from carrying bypassed EMP transients.
7. The use of MOS devices or latchup-prone devices should be avoided in interface circuits.

8. Where data upset cannot be tolerated, twisted shielded pairs should be used with high level common mode termination, redundant data transmission, or fiber optic links at interfaces.
9. Spark gaps on RF antenna transmission lines that operate in the EMP spectrum should be used.
10. Faraday-shielded transformers should be employed where transformers are necessary, such as audio or pulse interface lines.

In general, EMP protection should coordinate with good EMI, EMC, and EMV (lightning) designs. Measures that avoid separate treatments for similar transients are cost-effective.

THERMAL PROTECTION DEVICE(S)

The TPD should be mounted in a separate shielded enclosure within the unit. This prevents the EM field created when the TPD fires from propagating into the unit and causing damage. An example of a shielded enclosure is depicted in Figure 1. In this case, a printed circuit board (PCB) with a copper ground plane provides one wall of the shielded enclosure and the unit itself provided the other five walls and cover. The TPD return path is to the unit. Entry into the unit from the TPD enclosure should be through EMI/RFI filters.

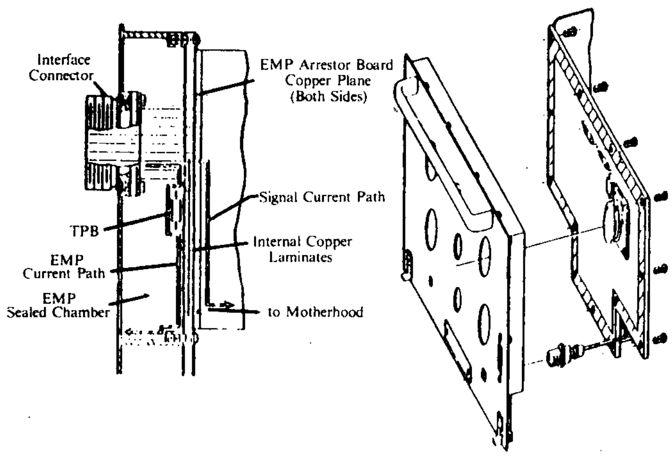


Figure 1. Mechanical Layout of TPD Shielded Enclosure.

Internal unit packages, layout and wiring should minimize loop areas and lead lengths into high-performance and high-gain circuitry. Parts with large junction areas and high power ratings are generally more resistant to EMP burnout than parts with small areas and low power ratings. Parts shall be selected with EMP susceptibility in mind.

Thermal protection device packaging techniques should be as shown in Figure 2.

EMP HARDENING

EMP hardening at the circuit level utilizes either protection devices or transient tolerant designs. EMP protection devices operate predominately in one of two ways: by clamping (limiting the magnitude of currents or voltages) or by filtering (removing energy in certain frequency bands). The important characteristics of some EMP protection devices are shown in Table 3.

Practical clamping devices for EMP protection, which are generally placed in shunt with the input lines, include a metal oxide varistor, diodes, and spark gaps. Clamping devices appear as a high-resistance shunt until the device threshold is reached, at which time the device becomes a low-impedance path and voltage is either clamped near the threshold point (varistor, diode) or drops to a lower value (spark gap).

A filter suppresses certain frequency components from EMP surge, thereby reducing the energy that sensitive piece parts must withstand. Clamping devices operate only above a specified magnitude or surge voltage, but

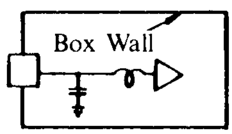
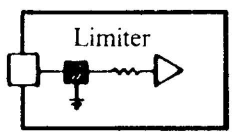
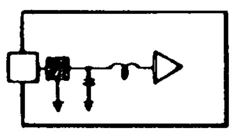
Hardening Technique	Illustrative Example	Operating Principle	Significant Design Penalties
Filter (discrete, filter pin, Incidental)	 Box Wall	Filters pass signals in selected frequency band and stop other signal transmissions.	Weight, cost, reliability
Limiters (Zeners, MOVs, spark gaps, resistors)	 Limiter	Limits voltage and thus energy applied to interface electronics.	Weight, cost, reliability
Hybrids		Combination of filters and limiters.	Weight, cost, reliability

Figure 2. Thermal Protection Device (TPD) Hardening Techniques.

Device Type	Clamping (or Filtering) Thresholds	Operate Time (s)	Highest Burnout Energy Threshold (J)	Shunt Capacitance (F)	Typical Circuit Applications	Possible Disadvantages
Varistors						
MOV	40-1500 V	$<10^{-9}$	$<10^{3}$	10^{-9}	Power, AF	High Capacitance
Semiconductors						
Forward Diodes	0.2-0.6 V	$<10^{-9}$	$<10^{1}$	10^{-12}	AF, RF	Low Burnout Energy
Breakdown Diodes	2-200 V	$<10^{-9}$	$<10^{2}$	10^{-8}	Power, AF	High Capacitance
Spark Gaps						
High-Speed Gaps	550-20,000 V	$<10^{-9}$	$<10^{3}$	10^{-11}	Term, AF, RF	Power-follow, High Cost
Arresters Using High-Speed Gaps	550-20,000 V	$<10^{-9}$	$<10^{3}$	10^{-11}	Power	High Cost
Filters						
Ferrite Chokes, Beads	RF	—	—	—	Power, AF	Ineffective Protection, DC Saturation
Feed-through Capacitors	RF	—	—	—	Power, AF	Dielectric Breakdown
General RLC Circuits	DC,AF,RF	—	—	—	Power, AF, RF	Impedance Mismatching

Table 3. EMP protection devices.

filters respond to specific frequencies regardless of magnitude. They can thus suppress spurious frequencies that might cause system upset, even if the interfering transient is not strong enough to activate a clamping device.

Devices used to implement transient protection must be rugged enough to withstand the transient and must be compatible with circuit operation. Some of the more important considerations are maximum operational voltage excursion, bandwidth, or bit rate, allowable capacitive load, circuit function, and the induced EMP waveform.

Transient-tolerant designs fall into three categories: hardware, software, and procedural. Hardware design techniques are useful for hardening against component damage and circuit upset, whereas software and procedural techniques are only useful for hardening against EMP upset. Transient-tolerant hardware design techniques consist of using circuit components such as relays (without suppression diodes), transformers, optical isolators, series bifilar chokes, and redundant system elements.

Software hardening measures are most useful for computer elements. For example, the use of plausibility checks on data is quite mundane, yet very effective as a means of "filter" data made erroneous by EMP-induced upsets. Another hardening measure, called checkpoint and rollback (CPRB) provides a means of tolerating logic upsets due to EMP. Error detecting and correcting (EDC) codes can be an effective hardening measure against EMP-induced upsets by allowing toleration of data errors caused by these upsets.

All of the hardening measures discussed above involve hardware or software implementations. To support these measures, EMP operational procedures should be instituted for the day-to-day operation of the system. The operation and maintenance staff should be educated on the effects to the system as a result of EMP transients. Operational procedures should be developed to recognize and recover from these effects when they occur.

COMPOSITE HOUSINGS

Composite housings will work in an EMP environment. However, certain tradeoffs will be necessary. Copper plating or copper flash with chem film will have to be on the interior and exterior of the housing. Depending on the EMP voltage specification, it may be necessary to add other EMP protection for the environment.

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