ELECTROMAGNETIC PULSE (EMP)

GENERAL CONSIDERATIONS

An electromagnetic pulse (EMP) is one of the products of a nuclear detonation. It presents a threat to exposed components since it can disable or cause malfunction in electronic equipment which is beyond the range of nuclear weapon's heat, shock and other radiation effects. It takes the form of electrons from the outer shells of air atoms which (as a result of the detonation) are given suitable energy and are free to travel until they recombine with another nucleus. During the time of the free travel, the electrons are bent into orbital paths by the earth's lines of magnetic force. The net motion of all the free electrons is an electric current whose effect is to generate an electromagnetic pulsed field that induces currents in conductors at great distances from the interacting layer in the atmosphere. This EMP will also interact with the surface of the earth in such a manner as to produce large electromagnetic energies flowing on the surface and to a limited extent, penetrating the surface. Studies and tests have characterized the earth's surface as a "lossy dielectric" in this situation.

The EMP is defined as electromagnetic field intensity on a time base. Qualitatively the EMP produced by nuclear detonation is analogous to electromagnetic pulses from other sources, such as those from lightning or high-power pulsed radar. The important aspects of the pulse's threat is its short duration and sub-microsecond rise time. This fast rise time implies a wide excitation bandwidth and significant energy content at very high frequencies. Illumination by this powerful, fast rise time pulse can induce currents and voltages which can be harmful (in varying degrees) to all types of unprotected electronic systems. It can generate noise in an analog system or propagate spurious data in digital systems in a manner comparable to EMI. The effect of exposure to EMP falls into two categories, a malfunction or "upset" of operating electronic systems, or permanent damage by failure of a sensitive electronic device.

Protection of electronic systems can be effectively provided by completely shielding around the entire periphery of the system. In most realistic cases such a solution will not be practical, and in any case the shield must be penetrated (for system interconnections, for example) and such openings can admit EMP energy as well as the intended signal. To reduce the general idea to successful practice, therefore, requires an integrated design incorporating shielding accompanied by voltage and current surge arrestors, harness connectors with high quality RFI fingers and effective backshells to provide continuity for harness shields, and special filters where required.

In essence, the system design must be controlled to limit the presence of degrading coupling to the EMP; whatever energy is coupled must be confined to the outside of the system; whatever energy does penetrate to the interior (harness conductors) must be filtered or shunted to limit the disturbance to the system.

PENETRATION AND DISTRIBUTION MECHANISMS

An EMP is best described as a field of electromagnetic energy which propagates in the conventional manner. When a conductor intercepts this field, current will be caused to flow in the conductor. Such coupling current may penetrate into a system and cause an inward flow of disturbance energy. Common coupling and penetration situations are:

A. Exterior field to conductor.
B. Exterior field to interior field.
C. Exterior current to interior current.
D. Interior field to current.

When a current flowing in a conductor meets a branch in that conductor, the current will be distributed among the branches in accordance with the impedance of each branch. A description of this branching is called a distribution function. Examples of distribution functions are:

A. Current divided inside a cable.
B. Currents shunted from a conductor to a surface.
C. Currents distributed on a surface.
D. Currents distributed at an interface, e.g., at the connector of a box.
E. Currents summed by a branched cable.
F. Currents summed inside a component.

The overall purpose of an EMP study or design program is to identify and evaluate all coupling and penetrations related to a specific system. To evaluate the potential seriousness of such penetration, the pertinent distribution functions must be determined also. Using both penetration and distribution functions (they are collectively called transfer functions), the impact of an external EMP field on a sensitive component can be determined. The effectiveness of the solution to an EMP program can be defined as the hardness. This is the ratio of the expected value of current that causes the component to malfunction to the expected value of current fed to that component, expressed in decibels. Mathematically this number will be positive for a safe value. As an example, if a component is safe by 20 dB, the current expected at the box will be ten times less than the current at the threshold of malfunction (or permanent damage). It must be noted here that the definition of hardness is given in terms of expected or mean values. There is always some error and some variation associated with measurement and calculation of these currents. The designer must account for these variations (normally in a statistical manner) to establish his hardness design goals.

COUPLING AND PENETRATION MECHANISMS

The various coupling and penetration mechanisms that have been observed, calculated, measured, and which are to be expected in physical systems are:

A. **Coupling from fields**
   a. E-field antennas
      1. Extended surfaces
      2. Exposed structures, cables, wires
   b. Loop antennas
      1. Structures
      2. Cable tied at two points
   c. Holes in skins or broad surfaces

B. **Penetration from Sheet or Flowing Currents**
   a. Holes in otherwise complete conducting surfaces
   b. Discontinuities in conducting surfaces resulting from joining otherwise continuous elements.
   c. Less than totally conducting surfaces including:
      1. Braid, mesh, and perforated metal
      2. Very thin and low conductance surfaces.

As this listing indicates, an evaluation of energy coupled from fields can be obtained by the use of antenna and field theory. In a preliminary analysis the response of the exposed system can be developed from standard field theory relating to dipole and loop antenna responses. This is usually sufficient to give order-of-magnitude values of skin currents.

Although the EMP disturbance is encountered as a field, its main evidence is the flow of a current in conductive materials as the system responds to the energy coupled from the field. The conductors of disturbance current can be wires designed to carry current for other reasons, structures made of metal, shields and shunts deliberately selected to control EMP current flow, and conducting plasma in the form of EMP excited arc-overs.

SKIN CURRENTS

In is apparent, therefore, that the treatment of skin currents has (in most real cases) several intermediate steps before it becomes the "expected value of current fed to a component" mentioned earlier in the hardness calculations.

The most apparent of these steps takes into account the amount of shielding which is used on a cabling harness which shunts some (or all) of the skin current. In order for current to appear on the center conductors as a result of external drive on a shielded cable it must penetrate either the shield, the shield termination, or cracks between the backshell to connector to component mechanical assembly. For a given external shield current, the magnitude of current appearing on the center conductors is a function of the r.f. impedances of the shield layers, the internal conductors and the loading at the ends of the conductors.

A second type of intermediate step in the calculation of current at a component from external skin currents involves holes in a conducting surface. The skin current may drive holes in otherwise continuous conducting surfaces in such a manner to serve as source of radiation to the interior. That current which would flow uniformly if there were no hole must concentrate at the edges of the hole. The degree of current concentration (or divergence) is an indication of an apparent voltage when seen from hole. This drop becomes a driving voltage when seen from the inner surface of the conducting surface. The drop will make current flow around the hole on the inside of the surface. This current can couple inductively to local conductors passing nearby and can also couple conductively to their shields through ground points near the hole.

Various combinations of these field coupling, penetration and distribution analyses are essential in arriving at a basic understanding of the EMP weakness of a system. More than simply providing a qualitative estimate of hardness, this approach will identify the major problem sources in the system and focus on the efficient application of corrections.

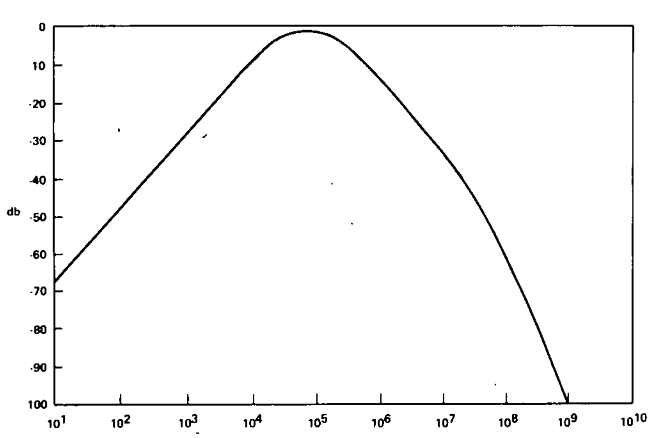
SUPPRESSING CONDUCTED EMP TRANSIENTS

EMP POWER & SPECTRUM

EMP pulses are characterized not only by high intensity but also by a broad range in the electromagnetic spectrum. RF energy produced in nuclear blasts span the range from commercial radio up through radar frequencies. This peaks out at about 100kHz and drops off substantially at 1GHz as shown in Figure 1.[2] Most military and commercial communication and radar equipment operate within this range.

Some components, such as vacuum tubes, resistors and capacitors, are relatively hard. However, semiconductors are quite sensitive to the fast electrical pulses generated by EMP. Burn-out levels for transistors, diodes, and ICs cover a broad range. Minimum observed energy levels to cause destructive effects occur as low as 10^{-7} joules for microwave diodes up to 10^{-1} joules for some audio transistors. Contrary to logical thinking, steady state power dissipation may not be indicative of ability to withstand fast rise-time, short duration EMP pulses. For example, a 30 joule rated varistor was destroyed with a 10^{-4} joule pulse from a simulated EMP source.[3] A 50 watt steady state rated zener diode can burn ou. with a pulse of 10^{-2} joules and a 10 watt steady state rated zener diode can burn out with a pulse of $5x10^{-3}$ joules.

For purposes of establishing a frame of reference, lightning has been compared with EMP, largely because of the historical information gathered in the study of meteoric electricity and its



Normalized Power Spectrum of EMP
Figure 1

effects on electronic equipment. Although lightning strokes are fast, 5 to 10 microseconds to crest, the transient voltage pulses induced into cables struck by a lightning discharge are stretched up to an order of magnitude or more. This transformation occurs because of the line inductance, end (termination) capacity, and the fact that lightning has a definite source of feed point. However, it is doubtful whether currents from distributive sources, such as EMP (or far-field lightning), would be stretched when conducted along cables.[4] Because of this difference, along with the high frequency energy present in an EMP, entirely new techniques must be considered when protecting against EMP exposure.

EFFECT OF CIRCUIT INDUCTANCE

Because of the fast rise-times of EMP, of the order of 5,000V/nanosecond and faster, inductive effects which generate voltage spikes described by the relationship

$$V = L\frac{di}{dt}$$

can be very significant. That which may appear to be negligible inductance, can be the source of voltage surges which can destroy sensitive components. Excessive lead lengths in transient suppression devices may very well be the source of destructive effects from which the device was inserted to give protection! The magnitude of "overshoot" voltage, or pulse energy leakage, due to length of device interconnecting leads is graphically illustrated in the following controlled series of tests.

TransZorbTM* silicon transient voltage suppressors were used in these experiments because of their fast "sub-nanosecond" response characteristics. The oscillogram in Figure 2 shows the open circuit voltage 5kV test pulse impressed upon the devices in subsequent surge tests and the oscillogram in Figure 3 depicts the 100A current pulse for the device under test. Because of the extremely low impedance of the suppressor under avalanche conditions, of the order of 50 milliohms, all devices in subsequent tests yielded approximately the same readout, approximately 100A, for current through the device. Suppressors of the 30V type, with varying lead lengths, were used to illustrate the effects of inductance in a transient suppression circuit.

Figure 4 depicts the overshoot (pulse) voltage produced under a 5kV pulse by a 30V silicon avalanche transient suppressor having 3 inch leads on each end. The magnitude of the voltage spike generated by the inductance in the leads is about 1200V peak and 20 nanoseconds in length.

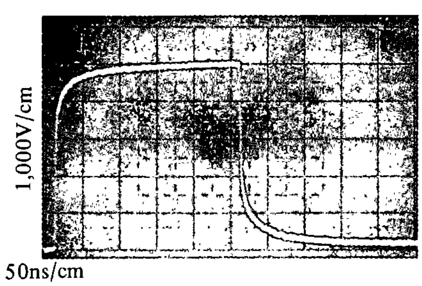


Figure 2—Voltage Test Pulse

5kV Pulse

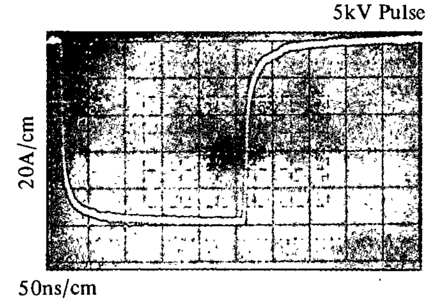
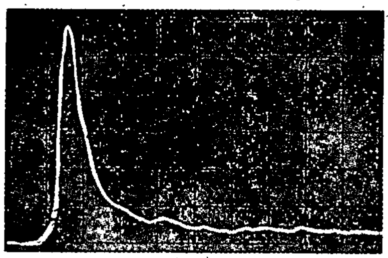


Figure 3—Current Pulse Under Test Load

*TransZorb—Trademark of General Semiconductor Industries, Inc.

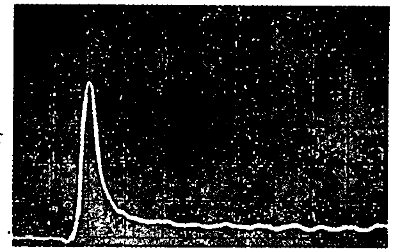
5kV Pulse



200V/cm

10ns/cm Figure 4

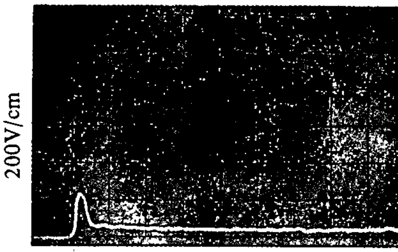
5kV Pulse



200V/cm

10ns/cm Figure 5

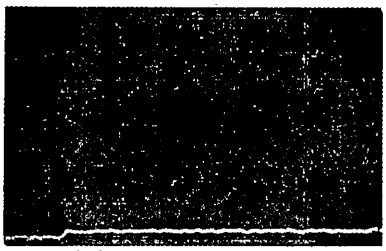
5kV Pulse



200V/cm

10ns/cm Figure 6

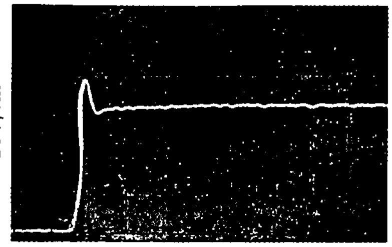
5kV Pulse



200V/cm

10ns/cm Figure 7

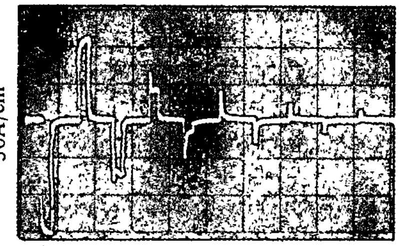
5kV Pulse



10V/cm

10ns/cm Figure 8

10kV Pulse



50A/cm

2 us/cm **Damped Current Pulse**

Figure 10

The energy of this pulse produced in the protective circuit using the relationship

$$E = \int P\, dt$$

is calculated to be $1.5x10^{-4}$ joules. An EMP pulse of this magnitude will burn out FETs and some types of switching transistors.

The next oscillogram (Figure 5) shows the overshoot of the same device also under a 5kV pulse except with 1¼ inch leads at each end. Reduction in lead length brings about a reduction in the inductive voltage spike. The voltage overshoot for this device is about 800V with a pulse width of 10 nanoseconds. Energy produced by this pulse is calculated to be $7x10^{-5}$ joules. EMP pulses of this magnitude will burn out FETs, microwave diodes and germanium diodes.

In Figure 6, the same device is shown except it is terminated at the package and is virtually leadless externally.

When the external lead lengths are reduced to zero, there is yet a measurable overshoot voltage contributed by inductance of the lead wires within the package itself. The energy produced by this inductance under a 5kV pulse is calculated to be $6.7x10^{-7}$ joules. This is sufficient to cause burn-out of microwave diodes.

By modifying the device package into a disc and removing virtually all of the inductance from within the package and simultaneously reducing inductance of the insertion method, the inductive overshoot is reduced even farther as shown in Figure 7.

The amount of energy leakage with a 5kV pulse is unresolvable from the oscillogram made with the same vertical sensitivity as for the previous tests. Figure 8 depicts the same device and conditions as Figure 7 except the vertical sensitivity has been reduced from 200V/cm to 10V/cm.

Energy leakage through this system above the clamping voltage is calculated to be $1.5x10^{-9}$ joules. This is below the threshold of destruction for semiconductor devices.

INSTRUMENTATION AND TESTING

The instrumentation shown in Figure 9 was used to generate simulated EMP pulses and to record the effects of those pulses on devices in the previous tests. The power supply delivers a square wave pulse of 250 nanoseconds duration (Figure 2) with a rise-time of 5kV/nanosecond from a 50 ohm source. All devices in these tests were surged with 5kV pulses.

It is interesting to note that power dissipation in the TPD is not all absorbed on the first pulse. Multiple reflections occur which bounce back and forth between the entrance end of the coaxial cable and the suppressor. Figure 10 depicts the damped current pulses under simulated conditions of 10kV EMP pulse.

EMP SUPPRESSION USING TRANSZORBS

Early studies performed under the direction of the U.S. Army Mobility Equipment Research and Development Center proved the feasibility of using silicon avalanche devices for EMP suppression.[5] This work incorporated the use of standard TransZorb product in the 1.5K6.8A through 1.5K200A series which are relatively new transient protectors on the market. These devices are characterized by small size and high transient power handling capability which is 1,500 watts for 1 millisecond up to 100,000 watts for 100 nanoseconds. Protection voltages available range from 5V through 200V for the standard product. Devices can be stacked in series to yield higher voltages as required. For higher power dissipation, devices can also be stacked in series or parallel depending on the design required.

Clamping of EMP is achieved through avalanche breakdown, a phenomenon which occurs when the device voltage is exceeded. Unlike SCRs and gas gaps, the voltage does not drop to a small fraction of the "striking" voltage upon initiating current flow. Hence, there is no need for a series voltage dropping resistor in dc circuits. The solid state avalanche phenomenon is fast. Figure 11 depicts a TransZorb (solid state avalanche device) protecting against a simulated EMP pulse of 5kV from the test setup as shown in Figure 9. The horizontal sweep has been resolved to 1 nanosecond per centimeter. It can be seen from this oscillogram that the clamping action is indeed rapid, in the one nanosecond range. The energy leakage of the pulse past this protective device is of the order of 10^{-9} joules, far below the threshold of damage to semiconductor devices.

REFERENCES

1. DNA EMP Awareness Course Notes. Prepared by IIT Research Institute, Contract No. DASA 01-69-C-0095/P.1. August 1971.
2. EMP Protection for Emergency Operating Centers. DOD/OCD Technical Report TR-61-A, May 1971, P. 11.
3. DNA EMP Awareness Course Notes. Prepared by IIT Research Institute, Contract No. DASA 01-69-C-0095 August 1971. P. 41.
4. EMP Protection for AM Radio Broadcast Stations, DOD/OCD Technical Report TR-61-C, May 1972, P. 8.
5. R. E. Gadberry and R. D. Winters, Feasibility Study into the
& Use of TransZorbs for EMP Suppression. Contract No.
6. DAAK 02-71-C-0127, USAMERDC, Oct. 1971.
7. O. M. Clark, and R. D. Winters, Feasibility Study for EMP Terminal Protection, Contract No. DAAG 39-72-C-0044, U.S. Army Materiel Command, Harry Diamond Laboratories, Nov. 1972.

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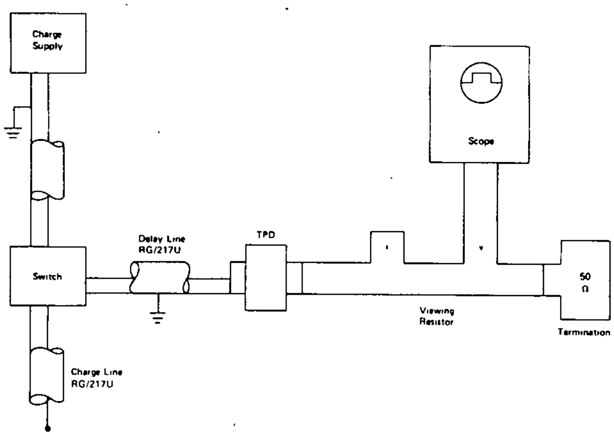


Pulse Generating and Measuring Equipment
Figure 9

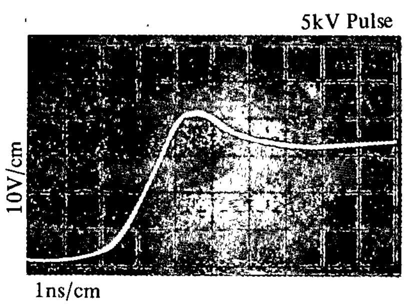
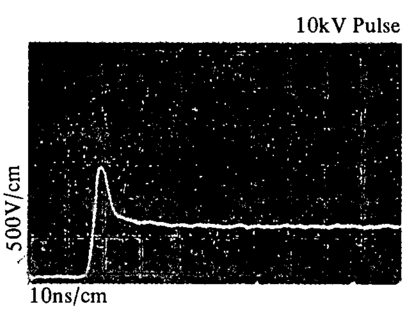
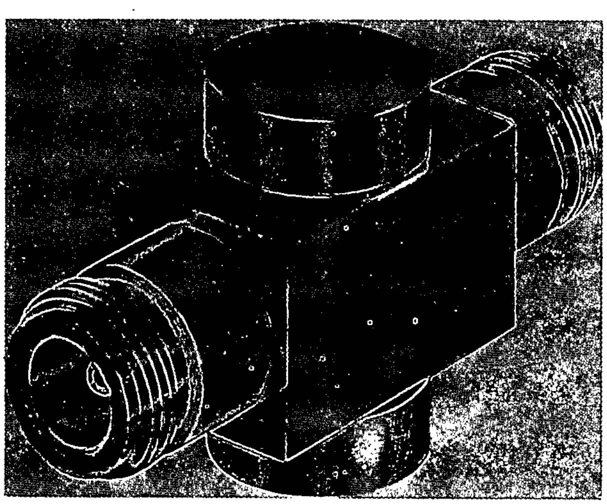


Figure 11



Missile System TPD Response Characteristics
Figure 12



Low Inductance TPD
Figure 13