Hardening Technique for Protecting of Electromagnetic Pulse Threat

iAkbal hanoon yahzi Technical institute Baghdad Iraq

***Abstract*— Electromagnetic pulses EMP are one of the most serious effects on modern electronic systems, so it should be taken into consideration when designing electronic systems. In this research was designed the way (Hardening Technique) to protect the systems from the effect of electromagnetic pulse (EMP).**

***Keywords*— EMP, Hardening Technique.**

I. INTRODUCTION

The electromagnetic pulse output from nuclear explosion, lightning, or other sources of EMP, is not generally considered to be one of the most destructive characteristic of an electronics system. So, when one considers that modern electronic equipment with its reliance on ultra-low power semiconductor devices can be easily damaged by electrical overstress at levels that can be produced many times over by an EMP, it becomes obvious that this is an output that must be taken very seriously indeed [1].

The Electromagnetic pulse EMP is a large threat on two counts; first an EMP is truly enormous, possessing amplitude of the order of tens of kilovolts per meter, a rise- time of the order of nanoseconds and duration approaching the microsecond region. Secondly, an EMP is very wide ranging, in that if it emanates from a weapon exploded outside the atmosphere, it is capable of covering vast areas of the Earth's surface, including complete continents, at a single blow. Clearly, significantly protecting or "hardening" equipment against its effects is essential for all systems, both military and civil, that must be relied upon should a nuclear war begin[2][3].From a project viewpoint, hardening equipment against the effects of EMP is a full engineering exercise. It must be considered through all its stages, starting right from the initial concept to its infield servicing and Maintenance. To give a greater understanding of why this should be so, Kendall Casey (Manhattan University) studied how EMP is coupled to shield cables [4].Willame E. Scharfrram worked on EMP coupling to power lines [5].Ghose from University of llinois [6] studied the EMP environment and Harding technique ,consider EMP susceptibility in electronic and weapons system which can be substantially reduced by effectively reducing the EMP coupling into systems. In this paper examines both the operation of the EMP threat and the requirements, techniques used to harden against it. Finally a more detailed examination of the typical project activities required is given.

A. Operation of the EMP Threat

Electromagnetic pulse EMP is a radiated electromagnetic threat. as it approaches an electronic system, all conducting parts of that system which come in contact with it will receive an induced current, typically as show in Fig.1 Defining the magnitude and form of this current is complicated as many factors, including the systems environment, are involved[7]. In general, those parts of the system, which have the largest dimensions also, receive the most current. For example, whereas typical currents on long land lines, large metal towers or similar can reach peak values of kilo amperes and above, typical currents on smaller structures, say two-meter whip antennas tend to be much nearer the two hundred amperes region. Note however the fast rate of rise of the EMP surge is maintained, at least initially, in both cases [8]. Large system therefore possesses an increased susceptibility to the EMP threat, due to their ability to collect and focus its energy from large areas of the Earth's surface, and it is these types of situations that would come under scrutiny [9] in a hardening exercise. The high energy density of an EMP does not allow the smaller parts of a system or indeed smaller systems to be protected [10].Although the externally induced currents represent the real Perceived strength of the EMP effects, they do not become a problem unless they are allowed to significantly permeate, and hence permanently damage, or permanently disrupt the sensitive circuits and components of the equipment they are induced upon. Hardening must prevent this possibility of upsetting the equipment [11]

Field threat (E, H)

System response (I_1, I_2, I_3, I_4, I_5)

Secondary coupling (i_1, i_2)

Component damage or circuit disruption

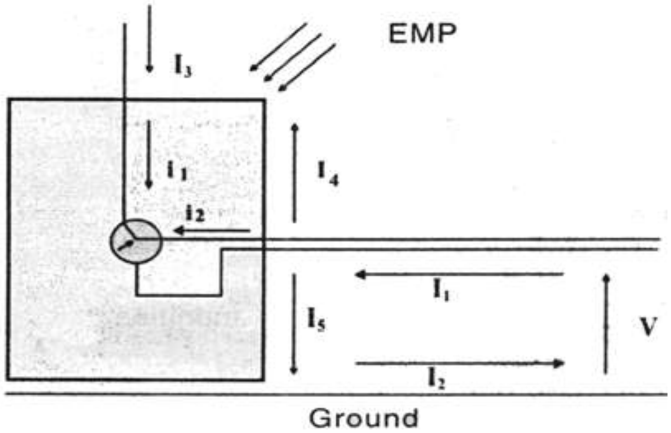


Fig. 1 A typical EMP Situation

Hardening therefore constitutes a balance between the magnitudes of the induced current on the one hand and the sensitivity of the equipment to be protected on the other, with the hardening measure employed acting as the fulcrum between them. As the induced current is equipment and system specific, techniques, such as system clustering and 'tree' or 'delta' interconnection schemes can be used to help reduce its magnitude. apart from this mention, a detailed discussion of the mechanisms of current induction is out of place in a paper such as this, and hence the investigation of the hardening balance will continue by examining the damage susceptibility of typical components.

B. The EMP Threat at Component and Circuit Level

Electromagnetic pulse transients which are picked up by an electronic system and propagated into the electronics or electrical circuits are generally short duration, damped sine waves with dominant frequencies[12], usually in the range of 100 KHz -100 MHz, Most Electromagnetic pulse EMP induced transients in electrical circuits are regarded as sources of temporary effects, although transients can lead to "latch-up" of a circuit or a semiconductor thus requiring a reset before transients, as signals may also be amplified in electronic circuits and the amplified signals in turn, may be interpreted as control signals, by the circuits. Such control signals in turn may result in a system malfunction by providing controls where they are not needed or by altering the degree of control. The sensitivity of digital circuits to upset by Electromagnetic pulse EMP transients depends on many factors such as.

- Magnitude of the" true" or "false" voltage level
- Switching time of the active semiconductors (rise time, storage time, etc.)
- Presence of background noise in the circuit due to nearby noise sources.
- Time of arrival of Electromagnetic pulse EMP transient with respect to docking wave form.
- Magnitude of resistance levels in circuits.
- Circuit inductances and capacitances.
- Magnitude of bias voltage in circuits.
- Schematic of the circuit and its physical layout.

II. LATCH-UP

Latch-up due to an Electromagnetic pulse EMP induced transient can occur when the transients flowing through the circuit cause a relay or switch to latch up [88]. A latch-up can also occur within the semiconductor. For example, the n-p-n-p or silicon -control-rectifier SCR can be latched into conductance by an EMP- induced transient, and the power into the circuit has to be removed to unlatch. Latching can also occur in an open base transistor circuit when the slope of collector current Ic against.Vce the voltage between the collector and emitter. Electromagnetic pulse EMP induced transient can move the operating level to point b, when the circuit becomes latched up at a high current level. The signal required to cause this event can be determined by noting that the Vce must be driven above the collector emitter breakdown voltage Vce. It should be noted that Ic-Vce characteristics of many transistor circuits are different from what is shown in Fig (2), since there is no reversal of the slope of Ic vs. Vce for such circuits. [13]

$$E = E_0 \left(1 + \sqrt{\frac{t}{t.}} + \frac{t}{\sqrt{t.\ t,}} \right)$$

The possibility of a latch-up of a circuit will depend on the type of circuit under consideration, and certainly many circuits do not latch-up. The susceptibility due to latching, therefore, may not exist in many cases. For cases where the possibility of latch-up exists, one has to trace the path of the EMP induced transient and determine the threshold signal for the latch-up either by an examination of the circuit or by a circuit analysis. [14]

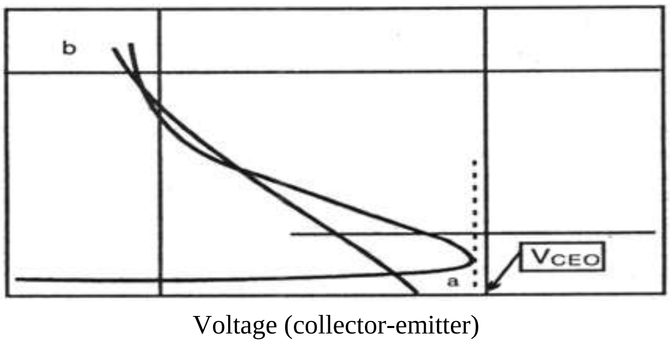


Fig. 2 Collector Current vs Collector-Emitter Voltage to illustrate Latch Up

A. Permanent Damages

In addition to temporary circuit upsets and latching, as discussed in previous sections, an electronic system can be affected almost permanently by EMP coupled energy. Particularly when such energy causes components burnout, there are various system components, which could be susceptible to burnout in an EMP environment, the most sensitive of which are the semiconductors. EMP induced burnout can, of course, occur also for other circuit components, such as resistor, capacitors, inductors, transformers, relay coils[15], vacuum tubes etc.The likely damages for semiconductors in an EMP environment are junction failures due to the excessive heating of the junction. The primary cause of failures of junction is believed to be the melting of the silicon in the junction due to high temperature. Furthermore, the junction temperature is not uniform because the current density is not uniform. This leads to hot support at the junction and hence weak points to cause a junction failure. In semiconductors, the damages in an EMP environment are believed to be caused most often by avalanche in the reverse breakdown direction, although the power required to cause junction failure in the forward direction is usually not much higher. For integrated circuits, the failure due to EMP could result from metal interconnection, oxide failure and latch-up of collector-to-substrate junctions.

Wunsch and Bell [16][17] developed a theoretical model for the junction failure due to the temperature rise, for one-dimensional heat flow corresponding to a plane junction in an infinite medium.

Based on such, a model for the reverse diode current and reverse base emitter current and a stepped-pulse type current input, a theoretical expression for the power per unit area-of a junction required to damage such a junction is given by.

$$\frac{P}{A} = \vec{K} t^{-1/2} \qquad 1$$

Where **K** is a constant function of time and, **t** is time in seconds. In Equation (1) K depends on the thermal conductivity **k**, density **p**, and specific heat **Cp** of the junction material. It also depends on the difference between the junction failure temperature $\mathbf{T_m}$ and the initial temperature $\mathbf{T_i}$ Thus.

$$\vec{K} = (\pi k_p C_p) t^{-\frac{1}{2}} (T_m - T_i) \qquad 2$$

Assuming typical values of the parameters given in Equation (2) as **k**=0.526 watt/cm- °**K**, **p**=2.33 gms/cm^3 **Cp**=0.7566 joule/gm°**K**, **Tm**=625°C (898 °K) and **Ti** =27°C (300°K), one may write from Equations (1 and 2)

$$\frac{P}{A} = 1109 t^{-1/2} \quad \text{for general} \qquad 3$$

Experimental data on diodes and transistors show somewhat lower values of K than 1109. They are, for example,

$$\frac{P}{A} = 560 t^{-1/2} \quad \text{for diode} \qquad 4$$

$$\frac{P}{A} = 310 t^{-\frac{1}{2}} \quad \text{for transistors} \qquad 5$$

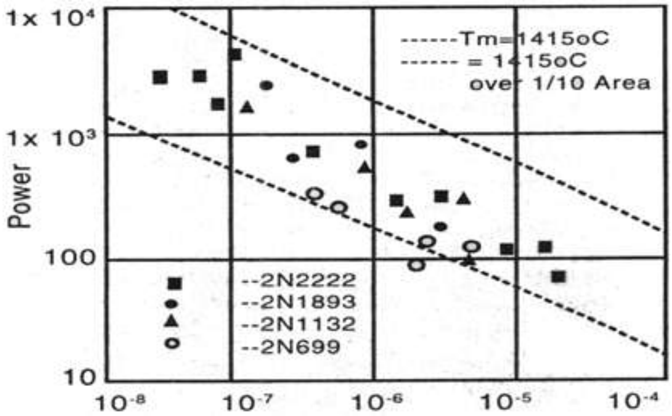
Although the expressions for P/A as given in Equation (4) are not accurate, they are probably valid within less than an order of magnitude.

This is illustrated in Fig.3 .Where the power per unit area in kilowatts/cm^2 corresponding to burnout is shown, as a function of time, for several transistors. [10]

A considerable amount of experimental data on the power required causing burnout damage to various diodes and transistors are now available. Expressing Equation (1) as

$$P = K.A.t^{-1/2} = C.t^{-1/2} \qquad 5$$

Experimentally determined density function of C for a wide variety of diodes, ranging from the very sensitive point contact diode, such as 1N82A to the powerful 1 N2824 is shown in Fig.4 a similar distribution of C for various transistors, ranging from the small 2N917 to the large 2N1722, is shown in Fig. 5. A more detailed breakdown of the ranges C for various semiconductor-device families [18] is shown in Fig.6.



Time in Seconds

Fig. 3 Power per Unit Area Corresponding to Burnout for several Transistors

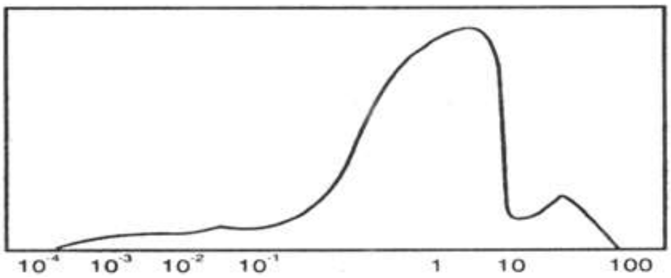


Fig.4 experimentally determined density function for a wide variety of diodes

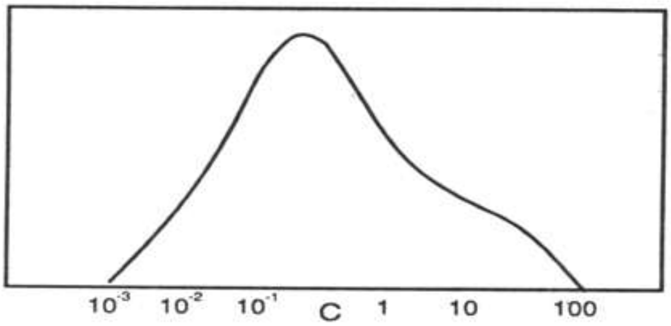


Fig. 5 Distribution of C for Various Transistors

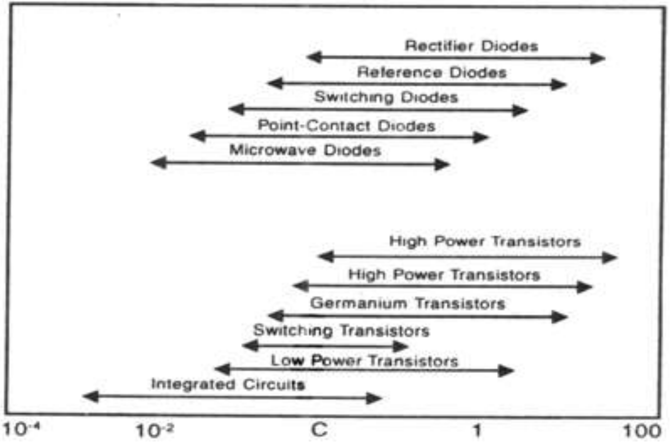


Fig. 6 Ranges of C of Various Semiconductor Devices

B. Dependance of Waveform and Pulse Duration on Burnout

The theoretical expression of P/A as given in Equation (1) is based on a stepped pulse type current input to the semiconductor devices. Since the EMP induced current input is not likely to be of the waveform assumed for the theoretical model, it is desirable to investigate the effect of other wave forms of input current on the burnout P/K Experimental studies conducted in this regard, so lead to the conclusion that the exact waveform of the damaging input current is not nearly as important as the general strength of the semiconductor device. Thus, the burnout data based on the stepped pulse input current as discussed in this section is quite useful in determining the expected behavior of the semiconductor devices in an EMP environment [19]. The time-dependence of the damaging power per unit area, as given in Equation (1) is valued when the EMP energy is applied to the circuit and rings down in about 10 nanoseconds to 10 microseconds. For much larger time duration (greater than 100 microseconds), the power level becomes time-independent, instead of a function of $t^{-1/2}$ For much shorter time duration (less than 10 nanoseconds) of the damaging current input, the burnout power level becomes inversely proportional to time.

To estimate the required burnout energy, one can integrate P for the duration of the pulse. For a square pulse of duration t:

$$E = P.t \tag{6}$$

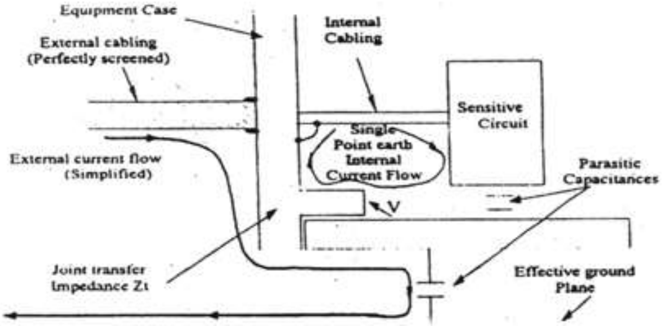
An energy representation of the failure threshold for different duration of EMP is shown in Fig .6.as seen in the figer, **E** is constant of $5x10^{-2}$ kilojoules for t<To. Where to be between 10 nsec to 1 psec, in the interval 10<t<10 psec. E is 10-^{1} milijoule x $t^{-1/2}$, t being in psec. For t>100μs, E is 10-^{2} milijoule x t^{-1}. [10]

III. PROTECTING AGAINST THE EMP THREAT

The approach most commonly used to harden a system I against damage from the EMP effects is conceptually easy to understand [11]. The approach involves grouping all sensitive components and circuits of that system into regions in which the electromagnetic environment is controlled, the degree of control depending on the component requirements. Each of these regions is then referred to as a zone[20], with the whole technique referred to as zoning. From the above description, it can be seen that zoning in its basic form involves the practice of generating screened volumes. As a screened volume is fundamentally any volume that is enclosed in metal, there will be instances in systems where the potential for such regions occurs naturally this is particularly true for military systems in ships, aircraft, personnel carriers and the like, and also for civil systems involving steel reinforced buildings, conduit trucking systems, etc. Whilst these may not satisfy all of the zonal requirements, they can certainly remove a lot of the sting out of the EMP threat, and much money and effort can be saved by making judicious use of them. Of course, it must be remembered that once they are designated as zones they must be treated as such, not only using the techniques to be described in this paper, but also in the later control of any prejudicial users' modifications that may occur. Also it almost goes without saying that any piece of equipment that is required to work outside these zones must be hardened separately [21].

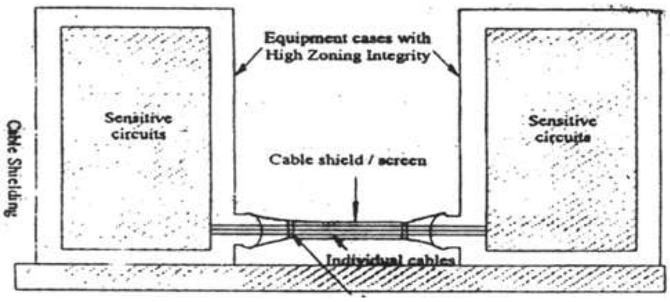
A. Hardened Zone Design

When designing a hardened zone, be it a screened room, vehicle or equipment case, two points must be approached. First, one must ensure that the metal surrounding the zone exhibits sufficient screening effectiveness and secondly, that the integrity of that screening is maintained around the boundary. As the first part is usually easy to obtain, the following discussion will concentrate on the second with particular reference to the control of aperture joints and cable penetrations. There are a number of ways in which control over apertures can be achieved without severely prejudicing their ability to provide visible access into the zone, First. They can be loaded with wire meshes of sufficient conductance that they effectively short circuit the holes. This method does require careful, low-impedance edge bonding of the mesh as the screening effectiveness of the mesh is highly sensitive to this parameter. A second technique available is to make use of the wave-guide beyond cutoff concept. This involves increasing the depth of the aperture (a depth to diameter ratio of 3:1 is normally recommended) and relying on the inability of such structures to support wave propagation when the free space wavelength is greater than twice the structures transverse dimension. Of course if this option is taken up, the aperture must not then be used as a convenient route for passing cables into the zone. [22][23].



V= internally generated voltage= Zt x external current (Laplace Domain)
Fig. 7 Internal coupling via a joint

Finally, as direct electromagnetic penetration of apertures is generally very small, the primary coupling mechanism results from the aperture's inductance being driven by the external currents. Therefore it is wise to keep Apertures away from regions of high external EMP current concentration, Furthermore, as the resultant coupled magnetic fields are concentrated close to the aperture, keeping wires, wire loops and components away from it will also help to minimize any damaging ingress[24]. To harden joints, the same care as exercised in the hardening of apertures must be continued. Simplification of the problem occurs however if the joint is not required to be broken, for in these instances the joint can be continuously welded, brazed or soldered. This is generally sufficient to ensure that penetration is kept to an acceptable minimum. When the joint is required to be broken, it must either be screwed or clipped together. This causes the joint to possess transfer impedance, akin to its contact impedance, via which penetration can occur. This situation is illustrated in Fig. 8. Which show how parasitic capacitances can cause internal current flow even when a single-point earthen scheme is used, a scheme that is essential for good EMP hardness. Therefore to harden joint it is essential to maintain good low transfer impedance. To obtain low transfer impedance joint, a number of requirement are involved. In the first place, it is necessary to ensure that the joint possesses a good overlap and is fixed at closely spaced intervals. Then it is necessary to ensure that the contacting surfaces have a chemically stable and compatible finish and finally that the metal is thick enough to avoid buckling. In cases where the joint is not well contacted (i.e. it is' holey') some relief from the subsequent poor high frequency shielding performance can be afforded by the use of a conducting gasket [25]. This relief however is generally accompanied by a decrease in low- frequency screening effectiveness.



Shield/Screen to Backshell Connection
Fig. 8 Cable Shielding

B. Hardening Cable Penetrations

Finally we now consider what is probably the most severe threat to the screening integrity of zone namely the problems associated with cable penetrations. In these circumstances, where significant cable pick- up cannot be avoided, direct penetration is inevitable. Although cable hardening is an involved process, it can be split up into three basic techniques. [26]

(a) Extending the zoning by screening the entry cables.

(b) Hardening the entry ports by including automatic switching devices (i.e. surge arrestors) and /or filters on each cable wire.

(c) Using non-conducting signal guides, such as optical fibers.

Zoning extension is good way of thinking about cable screening because what has already been said about zoning (e.g. concerning apertures and joints, etc.) applies to screens as well.Fig.9. Shows how cable screening is applied. This shows a screen connecting together two zones via two connectors with totally enclosed back shells. This turns the whole arrangement into one complete zone, of which the screen, connectors and all subsequent joints are an integral part. Therefore as much care must be exercised in choosing the connectors and their subsequent installation as must be exercised in choosing the screen.

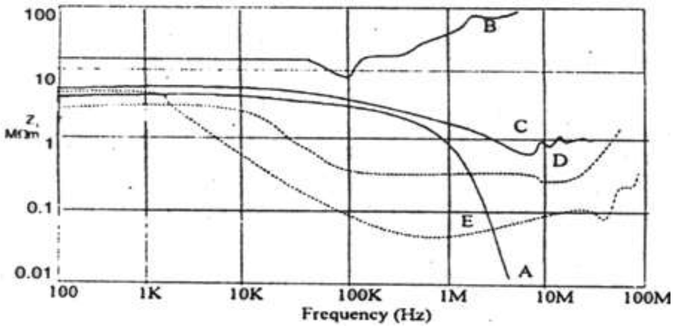


Fig. 9 Some Typical Performances of Cables Shields, where: A. Solid Screen, B. Single braid screen, C. Double braid screen, D. Double braid with interlayer of steel and E. Double braid with interlayer of mu-metal

In choosing screens, the main electrical parameter of interest is the screen's transfer impedance per unit length. This quantity relates the transverse electric field induced on the inside surface of the screen to the total current flowing on the outside surface. It therefore constitutes a direct measure of the screen's effectiveness [27].

Fig. 9 shows the measured transfer impedances for some typical cable screens. At low frequencies, these transfer impedances equal the resistance / unit length of the screens. As the frequency rises, skin effect takes over and the value of the transfer impedance begins to fall, either continuously, as in the case of solid screens, or until inductive penetration takes over, such as through the gaps of braided screens. For braided screens, the effects of skin effect penetration and inductive penetration can be made to partially cancel and this has led to a new class of epitomized-screens with improved high-frequency performance.

To improve on the performance of braided screens, screens incorporating tape wound ferromagnetic materials are used (see transfer impedances D and E of Fig. 9. By utilizing increased skin effect in these materials, these screens, or 'super screens' as they are called, can achieve transfer impedances as low as 50μΩ/m at 10 KHz. so, good as these screens are their use for EMP hardening tends to be limited to highly specialized applications as they are, in general, too effective for short cable runs and too expensive for long ones.

In fact, the method often used for hardening long cable lengths leads us neatly into the final method for cable hardening considered here, that of maintaining zoning integrity by the use of automatic switching devices and filters, either on their own, or as a back-up to cable screening. The type of devices that could be used are fast acting spark gaps (i.e. gas discharge tubes), specially designed zener diodes (i.e. Tranzorbs, TAZ diodes etc.) and varistors (voltage dependent resistors) These would be placed at both ends of the cable between each individual wire entry to the zone and some suitable ground reference. The devices, being non-linear and voltage activated, and then allow the surge entry to the zone to be controlled. Whilst simple in concept, the use of surge suppression devices does require careful consideration, the basis for which is laid out in.

IV. PROJECT ACTIVITIES IN PRODUCING AN EMP HARD SYSTEM

Now that the general operation of the EMPthreat has been discussed, it can be see why EMP hardening must be considered throughout all the stages involved in designing, developing building and maintaining a hard system.

The typical steps required can be summarized as follows:-

(a) Providing the actual threat environment has been fully considered, the first stage is to examine the basic system idea to generate in general terms how the system is to be hardened. It is at this stage that the system aspects of EMP hardening can be incorporated bearing in mind their possible conflicts with other design aims. The outcome of this task will in general be an EMP control plan.

(b) The next stage is to perform an initial assessment of the system to translate the requirements of the EMP control plan into a hardening design plan. If necessary, this plan would also include details of how the initial assessments are to be verified.

(c) Once prototype subsystems become available, more detailed tests can be undertaken. These can vary from damage or upset verification tests to the level of system tests using suitable EMP simulators. During this stage, consideration can also be given to developing a production control plan to contain such details as procurement specifications, detailed production drawings, assembly procedures and plans to perform the final certification tests.

(d) The final stage is then to develop a hardness assurance plan to maintain the system's hardness over its life cycle. This plan will typically contain details such as lists of approved parts, fitting and maintenance procedures and descriptions of operational procedures critical to the EMP hardness of the system.

The amount of work involved in each of these tasks is dependent on the system being hardened. However, the overall plan does represent a logical approach and if followed will result in the system possessing a very high probability of being successfully and cost-effectively hardened.

V. CONCLUSIONS

In this paper an overview of both the operations of the Electromagnetic pulse EMP threat and the techniques, aims and typical tasks required to harden equipment against it has been given. So an overview, the subject has been covered in general terms or, as in the case of test methods, omitted altogether.

As has been stressed throughout this paper, once the decision has been made to harden an electronic system, the effects of EMP must be considered throughout all stages of its development. If hardening is left to chance, the costs and problems of implementing it can grow significantly, if the correct decisions are made at the right time, hardening a system is neither inordinately difficult nor expensive.

REFERENCES

[1] Tasca, D.M, Power Failure Modes in Semiconductors, IEEE Annual Conference on Nuclear and Radiation Effects, July 1970.

[2] Electromagnetic Pulse Handbook for Missiles and Aircraft in Flight EMP Interaction 1-1, Air force Weapons Laboratory, September 1972.

[3] Miller, Colin R, Major, USAF “Electromagnetic Pulse Threats in 2010” Air War College, Air University, USAF.

[4] Dr. John, “How EMP Coupled to Shield Cables” University of Manhattan, July 1989.

[5] EMP coupling to power line by Williame. Scharfram (FEMA), 1990 August.

[6] EMP environment Dr. Ghose University Illinois, 1989.

[7] Hays, J. B., and Bodle, D. W., Electrical Protection of Tactical communications

[8] Uhilig, E.R., OCE NEMP Program, Development of Criteria for Protection of NIKE-X Power Plant and Facilities Electrical System against Nuclear Electromagnetic Pulse Effects: Protective Measures, General Electric Company, December 1967

[9] Brown, G. L., Ghose, R. N., Green, J. X., and Wounters, L. F.,Electromagnetic Pulse Energy Coupling Studies, ANC 30R-11, Vol. Ill, American Nucleonics Corporation, Glendale, 1967

[10] Wik, M., Kapp, W. H., Eggendorfer, A., Johl, W., Buchman, W.,Measurement and Application of Secondary Surge Arresters for the Purpose of NEMP Protections, fourth Symp. And Tech. Exhibition on EMC, Zurich, March 1981.

[11] EMP Protective Systems, Defense Civil Preparedness’ Agency, TR-61-B, July 1976

[12] Rabinowitz, Mario (1987) "Effect of the Fast Nuclear Electromagnetic Pulse on the Electric Power Grid Nationwide: A Different View".IEEE Trans. Power Delivery,
WRD-2, 1199–1222 arXiv: physics/0307127.

[13] EMP Protection for AM Radio Broadcast Stations (Glossary of Design Practices), Defense Civil Preparedness Agency, TR-61-B, July 1976

[14] Vance,E .F., EMP Hardness of systems, Fourth Symp. And Tech.Exhibition on Electromagnetic Compatibility, Zurich, March 1981.

[15]Clark, O. M., EMP Transient Suppression using the transzorb, general Semiconductor Industries, Inc., App., Note 1012, Tempe, Arizona, 1979.

[16] Engineer's Handbook for Configuration and Technical Data Management, Fort Belvoir, Virginia, December 1967.

[17]D. L. Wunsch and R. R. Bell, "Determination of Threshold Failure Levels Of Semiconductor Diodes and Transistors Due to Pulsed Voltages," IEEE Trans. Nucl. Sci. NS-15, 244 (1968)

[18] Brown, G. L., Keith, R. M., and Shkabara, P., Testing and Evaluation of Shielded Cables, ANC 30R-27, American Nucleonics Corporation, Glendale, California, April 1970.

[19] Brown, G. L., Ghose, R. N., Green, J. X., Putzer, E. J., Schwartz, K., Electromagnetic Energy Coupling Studies - Design practices, ANC 30R-7, American Nucleonic Corporation, Glendale California, February 1967.

[20] Green, J. X., and Brown, G. L., Hardness Assurance Program, ANC 30R-25, American Nucleonic Corporation, Glendale, California April 1970.

[21] Vance, E. F., EMP Hardness of Systems, Fourth Symp. And Tech.Exhibition on Electromagnetic compatibility, Zurich, March 1981.

[22] Ghose .Rabindra N, EMP Environment and system Hardness Design, Library of Congress Catalog Card Number 83-51062 (Don White Consultants, Inc, Gainesville, VA, 1984).

[23]Bailey, D.T. ET AL. EMP Hardening Guidelines, System Life Cycle Cost Design Considerations, AWFL-TR-161 (AWFL, May 1980).

[24] Karzas, W. J., and Latter, R. Electromagnetic Radiation from a Nuclear Explosion in Space, Rand Report No. RM-2849-AFT, October, 1961.

[25] Cowling, T. G., Magnetohydrodyn Symp. 4, New York Interscience Publishers, New York, N. Y.

[26] Stogryn, A. P., and Ghose, R. N., Generation of an Electromagnetic pulse by an Expanding Plasma, Radio Science Journal of Research, P. 147, Vol. 68D, No.2, February 1964.

[27] Baum C. F., Unsaturated Compton Current and Space Charge Field in Evacuated cavities, Air force Weapons lab, January 1965.