Section V

System Assessment, Hardening, and Life Cycle Maintenance

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Introduction to Section V

(U) The preceding two sections (III and IV) of this issue comprise a series of papers on various aspects of the technology which describes the EMP phenomenon that underlies the requirements for EMP hardening of systems. For this section, we discuss those hardening applications by presenting the range of options available to the designer and program manager for hardening, for validation/assessment, and for life-cycle maintenance of the deployed hardness.

(U) Most hardening approaches that have been implemented, to date, can claim some measure of improvement in either reducing the EMP stresses within the system or reducing the susceptibility of the internal electronics. However, the key technical issues to be resolved are whether the improvement is sufficient, whether the hardening can be verified, and whether the improvements can be maintained over the life cycle. Therefore, any hardening approach must be reviewed and discussed in concert with its associated validation and maintenance approach.

(U) Since the verification and maintenance implementation is so strongly affected by the hardening approach, the system designer has been confronted by differing opinions on what combination of approaches would best suit his system development. Some typical questions that result include the following:

1. "A system is hard (survivable) until it is demonstrated to be soft (vulnerable)."

   Versus

   "A system is soft until it is demonstrated to be hard."

2. "A reasonable probability of survival to EMP can be adequately verified."

   Versus

   "Survival probability cannot be well calculated; best to make it as close to 1 as technically feasible."

3. "For many systems, only EMP damage need be of concern; upset can be adequately dealt with by preset automatic or manual recovery procedures."

   Versus

   "The history of EMP testing has provided many examples of mission aborting upset-induced anomalies; these more often than not were not predictable modes of the system. Thus EMP hardness must include protection against all upset."

(U) These differing interpretations of "EMP hardness" have led to advocacy of "electronics or distributed hardening" on the one hand versus "integral shielding" on the other hand. In addition to interpretive (or perhaps subjective) differences, there are some real, but simple, technical differences between the two approaches. The electronics approach leads to moderate EMP transient stress reduction in general, with some stringent attenuation required for special, predictable cases. As such, it is argued, there is no "overkill" in the hardening solution. The integral shield approach admits to an overkill, but argues that there is no way of reliably predicting just where the increased protection is needed.

(U) The most significant underlying technical issues are the following:

1. The previously noted "damage versus upset" question.
2. If only damage is important, then what are reliable threshold values to use at the component or interface pin level? The electronics approach generally relies on having damage levels higher than normal operating levels, leading to only moderate stress attenuation for most interfaces. If, in fact, appropriate bounds for damage thresholds were near the normal operating levels, then the distinction between "electronics" and "integral shield" would practically vanish in terms of the attenuation requirements; the only remaining distinction would be the distribution of that protection within the system.
3. How reliable is analysis, as opposed to test, as a tool for validating the designed and implemented EMP protection? How does one deal with the problem of the very large numbers of predictions or test results which can be required by designs

which distribute the protection deep within the system to the subsystem interface levels?

4. Finally, how does one practically maintain the deployed hardness if it depends on a very large number of elements retaining their deployed characteristics?

(U) To illuminate, if not provide solutions to, these issues, in this section we have first a paper by Morgan, Vance, and York which discusses the range of EMP hardening options available to the design engineer, followed by Schaefer's discussion of validation procedures a they relate to different design options. We note that Schaefer requires complete test validation of hardening protection at every interface and does not consider the use of analysis and statistical sampling in his procedures. A paper by Mo discusses, with illustrations, some of the constraints imposed on conclusions from test data when appropriate statistical theory is applied. A three-part paper by Dubois, Merewether, Reed, and Morgan treats both managerial and engineering aspects of hardness maintenance and surveillance, focusing on the transient stress-reducing hardware (shields, filters, terminal protection devices) rather than on the logistics aspects of maintaining subsystem EMP hardness. Finally there are two papers which present views on how choices should be made from this menu of engineering options to formulate a program for achieving EMP survivable systems.

(U) Gage, Wallace, and Wunsch argue for a "systems requirement approach" and present a formalism for contractual specifications and a discussion of applying quantitative systems analysis to meeting these specifications. The interrelation of EMP hardening with other system requirements is emphasized, and a six-task procedure is outlined which envisions systematic alternative design studies with quantitative cost-effectiveness results, enabling the final choice of hardening programs to be optimized. The authors argue that the approach is viable at present by citing some studies of the kind of information available in today's data base, but do not present a quantitative discussion of this data.

(U) The final paper, by Karzas and Bell, presents a view, by arguing from historical evidence, that there is a preferred EMP hardening solution for both new and existing systems which uses today's tools and data base—the integral shield with minimized controlled penetrations—and that this solution has many attractive features for reducing life-cycle costs as well as providing EMP protection with low risk.

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EMP Hardening Design Approaches (U)

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(U) Electromagnetic pulse (EMP) hardening design consists of identifying and developing electromagnetic barriers against direct and induced EMP waves. These barriers typically consist of shields to exclude waves propagating through space and filters or other devices to exclude waves propagating along wires that penetrate the shield or propagating through openings in the shield. The roles of filters, surge arrestors, waveguides beyond cutoff, and other barrier elements in EMP hardening are discussed. Thresholds for EMP protection are also discussed, and their implication on validation, maintenance, and hardness surveillance is developed. When EMP protection is distributed between two barriers (one at the system level and one at the box or equipment level), the way the protection is allocated affects the ability to evaluate the protection, as well as the supporting maintenance and surveillance requirements. Because EMP stresses are not experienced during normal peacetime operation of the system, system operators get no feedback on whether the system hardness is functioning or not. Thus, an artificial feedback system that indicates compromises in the protection is useful. The effects of barrier shape, topology, complexity, fragility, and other characteristics on the ability to evaluate the protection, maintain it, and support it under operational conditions are also discussed. It is concluded that the EMP-unique protection should be applied to the outermost levels and should be rugged and relatively tamperproof so that normal military use and maintenance do not cause its degradation.

INTRODUCTION

(U) The protection of systems against the nuclear electromagnetic pulse (EMP) is fundamentally similar to other interference control problems; it involves preventing the source (the EMP) from interacting with the potential victim (usually an electronic circuit) in an unacceptable way. There are several general ways of solving this problem (see Fig. 1):

- (U) The source and victim can be separated by an infinite distance.
- (U) The source and victim can be orthogonalized so that they cannot interact.
- (U) The source and victim can be separated by an impervious electromagnetic barrier.

(U) In theory, we can also eliminate the source or eliminate the victim. However, when the source is the EMP, we cannot rely on eliminating the source, and we assume here that any unnecessary victims have already been eliminated, so that the EMP control methods remaining are physical separation, orthogonalization, and placing a barrier between the EMP and the system to be protected. The first two control methods can be used as elements of barriers in some cases. Other schemes, such as weakening the source or making the victim more tolerant, are almost always an application of one of the barrier techniques to the source or victim.

(U) The electromagnetic barrier is a surface that completely encloses either the source or the victim, as illustrated in Fig. 1c. The ideal barrier is a perfectly conducting shield; no electromagnetic events occurring outside the shield can be detected inside a closed, perfectly conducting shield. In practice, we have neither perfectly conducting shields nor completely closed, continuous shields, because we must supply energy to the system inside the shield, get information into and out of the system, remove excess heat, and so forth.

(U) Thus, even if we had a perfectly conducting shield, a penetrating wire, as illustrated in Fig. 2a, can

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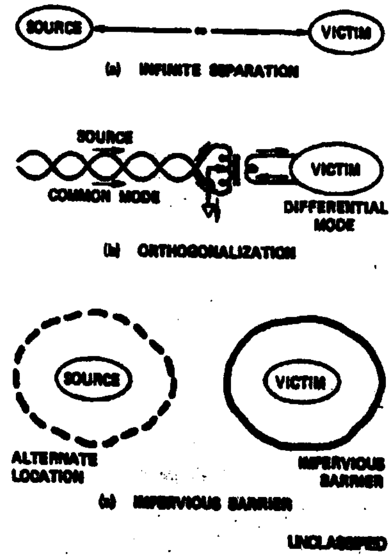

Figure 1. (U) Interference control concepts.

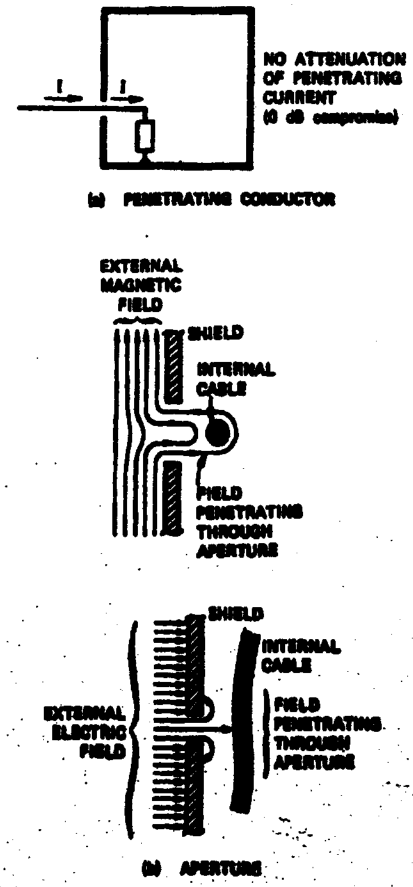

Figure 2. (U) Compromises of shield.

negate the effect of the shield, since the externally induced current passes through the shield unattenuated. Windows and other holes in the shield (without penetrating conductors) also allow external fields to penetrate, where they may interact with internal wiring (Fig. 2b). The interaction through apertures is usually much weaker than through penetrating conductors, since coupling through apertures is like a small, mutual capacitance or mutual inductance between the internal wiring and external structure, whereas the penetrating conductor is a hardwire connection from the interior to the exterior. The maximum voltage that can be induced in a single-turn loop inside a shield by magnetic coupling through an aperture is the voltage developed across the aperture (see Fig. 3).

(U) If we had no penetrating wires or apertures, but used ordinary metal shields instead of superconductors, this compromise would usually be negligible. One millimeter of common metal such as steel or aluminum is usually sufficient to reduce the EMP-induced transients in the circuits inside the shield to a value considerably less than the system itself produces.

Table I shows the open-circuit voltage induced in the largest single-turn loop that can be placed inside a spherical shield of 10-meter radius for various wall thicknesses and materials. The 50-kV/m plane-wave exponential pulse with 250-nsec decay time constant is incident on the shield. Note that with walls only 0.2 mm (8 mils) thick, the induced voltage is less than

1 volt for these common materials. Hence, unless the shields are very long and slender (for example, cable shields) or the internal circuits are sensitive to low-frequency magnetic fields, the finite conductivity of ordinary metals is not an important compromise.

(U) Because the shield conductivity and thickness are seldom important considerations in designing EMP protection, we often speak of electromagnetic barriers that consist of the shield, filters, and other surge limiters (which are impervious to the waves propagated along wires and pipes), and aperture treatments, such as waveguide-beyond-cutoff applications to windows or other openings, gaskets on doors and access hatches, and various other devices designed to form a surface impervious to external waves. Most of the EMP protection design effort is therefore directed toward the wire and aperture treatments.

(U) The goal of EMP hardening is to develop barriers that are sufficiently impervious to the EMP to ensure system protection and that are also economical, reliable, and maintainable in an operational environment.

APPLICATIONS TO SYSTEMS

(U) Many military systems are constructed with metal exteriors that may be adapted for use as an EMP barrier. Natural barriers, such as those illustrated in Fig. 4, almost always contain sufficient metal of adequate conductivity to serve as the shield element of the barrier. Usually, however, they are not closed barriers; they may have many wires, hydraulic lines, control cables, and other conductors that penetrate the shield, and they may have many windows, doors, and hatches that allow the EMP fields to interact with the interior. There is seldom an electromagnetic shielding requirement on the aircraft skin, ship's hull, or other system-level structure.

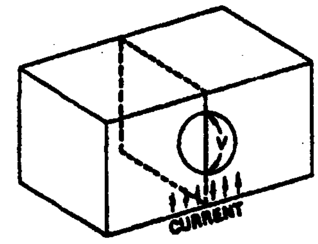

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Figure 3. (U) Coupling through an aperture.

(U) On the other hand, the equipment (usually inside the natural system-level shield) almost always has a shielding requirement. Most military electronics units must meet interference susceptibility and emission

TABLE I. (U) *Shielding by diffusion.*

Shield Thickness (mm)	Internal Voltage Induced in Loop* — Copper $\sigma = 5.8 \times 10^7$ mho/m	Aluminum $\sigma = 3.7 \times 10^7$ mho/m	Steel $\sigma = 6 \times 10^6$ mho/m ($\mu_r = 200$)
0.2	0.34 V	0.85 V	0.076 V
1.0	2.6 mV	6.4 mV	1.1 mV
5.0	21.0 μV	51.0 μV	15.0 μV

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*Peak voltage induced in a loop of radius 10 m inside a spherical shield of radius 10 m illuminated by a high-altitude EMP (by diffusion through walls only).

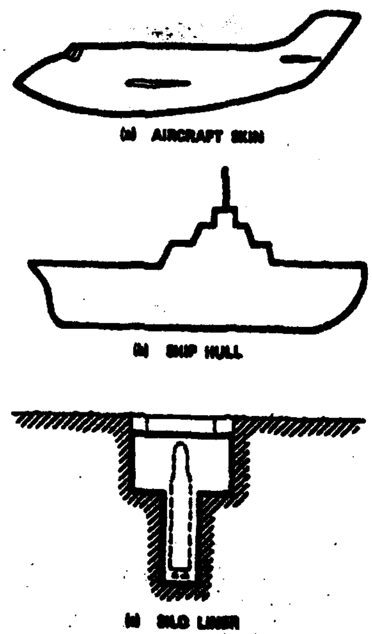

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Figure 4. (U) Natural barrier elements.

requirements; they must withstand system-level sources outside the unit, and they must not unduly contaminate the electromagnetic environment outside the unit. Thus, each unit has its own barrier, usually built around its metal case as illustrated in Fig. 5, that excludes external interference and confines the interference that its internal circuits generate. The goal of the electromagnetic compatibility standards is to ensure that such equipment tolerates, but does not contaminate, the peacetime operating environment.

(U) To adapt the natural system barrier, such as an aircraft skin, for use as the EMP barrier, all openings in the metal structure must be identified, and appropriate measures to close the electromagnetic barrier at these points must be developed. On conventional aircraft, for example, the conductors penetrating the hull from exposed areas, such as bomb bays, wheel wells, open areas of the wings, must be treated in such a manner that the EMP barrier is closed about these

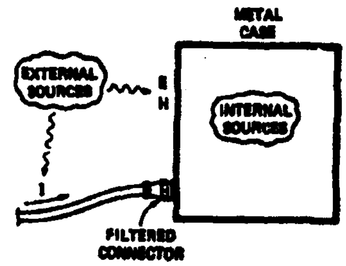

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Figure 5. (U) Equipment level barrier.

wires, tubes, cables, ducts, and so forth. Windows, doors, and other large openings must also be identified, examined, and possibly treated to reduce EMP interaction through them with interior wiring and structure.

(U) The objective of the barrier closure is to keep externally induced currents and associated fields out of the protected space. Thus, the treatment of penetrating wires, cables, pipes, and so forth may consist of diverting the wire (or other conductor) current to the shield (Fig. 6a), interrupting the current (Fig. 6b), or by orthogonalization (Fig. 6c) so that, for example, the interior circuit responds only to the differential-mode signal, while the EMP induces only a common-mode current on the exterior circuit.

(U) Pipes, waveguides, ground wires, and other conductors that can be continuously connected to the shield may be welded or otherwise peripherally connected to the shield where they penetrate to divert the EMP-induced current to the shield (as illustrated on the right of Fig. 6a). Signal and power wires cannot be continuously connected to the shield, but they can be momentarily connected through a surge arrester when the voltage exceeds a predetermined threshold, or they can be connected to the shield outside a passband through a filter.

(U) Current interruption (Fig. 6b) can be implemented by using plastic pipe or tubing for plumbing penetrations, certain types of filters, and optical or dielectric waveguide isolators. However, because the open-circuit voltages induced by the EMP on long external conductors are very large, current interruption at the system level should be used with caution.

(U) The most common form of orthogonalization is

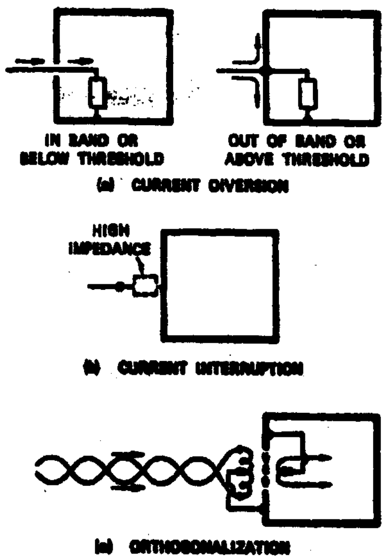

Figure 6. (U) Barrier elements on wires and cables.

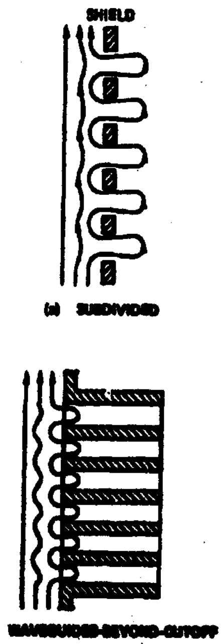

Figure 7. (U) Reduction of fields penetrating apertures.

the common-mode rejection in balanced circuits (Fig. 6c). This is an effective and economical method of protecting circuits from interference induced on interconnecting cables. It can also be used on some power penetrations (usually in conjunction with other devices), as well as on signal pairs. The common-mode current may be either diverted or interrupted, as was the case for single-conductor currents, and with the same considerations as for single-wire currents.

(U) Several methods are available to close the barrier at large openings in the shield. Here the goal is to minimize the electromagnetic fields penetrating these windows, vents, and so forth. Some openings can be closed with a conducting cover. Those that cannot be covered may be converted into waveguides beyond cutoff, subdivided into many small apertures with a perforated sheet when passage of air or light are important, or subdivided and treated with many small waveguides beyond cutoff. The last two methods are illustrated in Fig. 7.

(U) Evidently, these methods of treating penetrating conductors and apertures can be implemented in many ways with varying effectiveness and reliability. One problem facing the designer of EMP protection is to determine how much protection is needed. The lower bound on the amount of protection required seems to be that amount that will at least prevent unacceptable damage to the system. On the other hand, if enough protection is provided so that the EMP-induced stress is not the dominant stress inside the EMP barrier, further protection will not improve the EMP immunity of the system, since system-generated or other non-EMP stresses are already larger than those induced by the EMP. The next section discusses the implications of the various allocations of protection, barrier shapes, and other peculiarities of protecting systems against the EMP.

EMP PROTECTION OPTIONS

GENERAL

(U) As noted above, many systems have natural barrier surfaces at the system level and at the equipment unit or box level. Furthermore, some interference and compatibility controls already exist at the unit level. It seems logical to take advantage of this existing system-level structure and unit tolerance in designing EMP protection, that is, to allocate the protection between these two levels.

(U) Before discussing specific allocations, it is useful to consider some of the factors that affect our choices. Consider, for example, an all-metal aircraft. A barrier could be formed at the skin having only a few dozen penetrating conductors—mostly communication and navigation antennas—and perhaps the cockpit windows. If all the EMP protection is placed at this level, and the EMP-induced stress is not dominant inside this level, only the interaction of the EMP with the exterior of the aircraft and these antennas must be understood to design and evaluate the protection.

(U) However, if the protection is allocated to the equipment units inside the airframe so that each unit has a specific EMP requirement, an understanding of a much higher level of interaction complexity is required. A typical large transport or bomber aircraft contains several thousand line-replaceable units, each of which interfaces with the aircraft or other units through (typically) 20 or 30 connector pins. Thus, to design and evaluate EMP protection at the unit level, one is obliged to understand the EMP interaction deeper in the system and to understand the interaction with tens of thousands of circuits.

(U) In general, the deeper into the system the EMP requirements are specified, the more complex the EMP interaction one must cope with becomes. In addition, the number of systems or circuit states also increases drastically as we go deeper into the system. At the aircraft skin, only a few states are important (those associated with gear up or down, bomb bay doors open or closed, VLF antenna extended or not, ground power attached or not, and so forth). Inside the aircraft (but outside the units), there are many additional states. These are associated with the hundreds of switches, relays, and circuit breakers that control aircraft power and systems. Inside digital electronics units, the circuits can have unimaginably large numbers of states—a one-kilobyte processor has 2^{8000} states. While many of these states are unimportant or have the same threshold, sufficient understanding must be acquired to determine which are unimportant or have common thresholds. The sheer numbers involved deep in the system make the probability of significant oversights worrisome.

(U) Conversely, if determination of the system threshold (at the system level) requires an understanding of all of the internal interaction to transfer solid-state-device thresholds to the system level, then there is no advantage to applying the EMP protection at the outer level, because the complexity of translating thresholds outward to the skin is about the same as the complexity of transferring EMP interaction inward to the circuit. However, the threshold transfer is necessary only if the EMP-induced stress is the dominant stress deep in the system; presumably, if the normal operation of the system itself produces stresses greater than those induced by the EMP, one does not need to understand the EMP interaction to know that the system will tolerate the weaker EMP stress (assuming that the system normally functions properly). Hence, it is possible to know that the system will withstand the EMP stresses without understanding the detailed responses of the complex interior of the system.

(U) In addition to the circuit complexity and states problems just discussed, there is another contributor to the complexity problem: the number of modes of excitation. Although the unit with a 20-pin connector may have 10 to 20 signal and power drive modes, there are 400 ways the pins can be driven two at a time in the general case where nonlinear circuits are involved. Since the EMP is not obliged to interact with the unit and its cabling in the same way that the normal operating signals do, it may be necessary to understand the unit response (or threshold) to all these excitation modes (and perhaps three-or-more-pin modes) if the EMP-induced stress is the dominant stress at the unit. Again, the possibilities for oversights are enormous if understanding the interaction of large numbers of pins or penetrating wires is required to design and evaluate the EMP protection. Thus, there is a strong desire to minimize this uncertainty and alleviate validation concerns by minimizing the number of penetrating wires that must be understood, treated, and evaluated.

ALLOCATION

(U) Although there are an infinite number of possible divisions of the protection between the two natural barriers (the system shield and the equipment case), only four possess distinctly different characteristics. In two of these, all protection is allocated to one barrier; in the other two, part of the protection is allocated to each barrier. The principal differences in their characteristics are the complexity of the EMP interaction that must be evaluated and controlled and the amount of configuration control needed to maintain the protection.

Single System-Level Barrier

(U) Consider first applying all the protection to the system-level barrier and allocating no protection to the internal units. This usually implies that the units cannot be relied upon for EMP tolerance, so that the system-level barrier must reduce the EMP-induced stress to well below the system operating signal levels. This is illustrated in Fig. 8 by the bold system border and the dashed unit borders.

(U) The single system-level EMP barrier has the advantage that no elements inside the barrier must meet any specific EMP requirement. Thus, there are no configuration control problems inside the EMP barrier, and no special equipment must be flagged and stocked separately for the EMP-hardened systems. The latter is important for hardness maintenance and operating economy. It eliminates the cost of maintaining an inventory of special EMP units throughout the life of the system, and it eliminates the possibility that an unhardened standard unit will be substituted for a functionally equivalent special EMP unit at some point in the operational life of the system. Finally, modifications and equipment changes inside the EMP barrier can be made in the future without redesigning the system EMP protection, since there are no EMP requirements on internal units and structure.

(U) In addition, the single system-level barrier can be made with a minimum number of penetrating wires and relevant system states. Thus, the testing and analysis required to ascertain that the EMP protection performs properly are more tractable and less time consuming. Similarly, a more comprehensive hardness-surveillance procedure can be established, since there are fewer "failure possibilities" to monitor.

(U) The disadvantages of the single system-level barrier are that it requires integration of electromagnetic protection with structural, control, hydraulic, and other functions to form a single closed barrier and maintain this barrier throughout the life

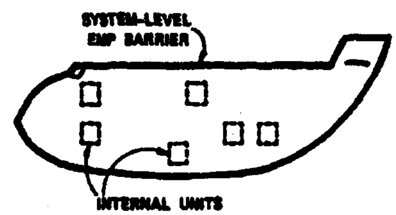

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Figure 8. (U) All EMP protection at system level.

of the system. Because a fairly high-quality barrier is required to suppress the EMP to the levels needed for this allocation, the barrier is somewhat more susceptible to compromises that result from negligence or poor maintenance. Because the unit tolerance for interference is assumed not to be applicable to the EMP, this allocation does not take advantage of the inherent immunity of the units.

(U) It is also alleged that the single-barrier allocation is more costly to implement than some other allocations, but it is difficult to compare costs that are derived from dissimilar projects with dissimilar objectives. Some believe that any higher initial cost is offset by lower operating costs and greater assurance that the EMP protection is functioning.

Single Unit-Level Barrier

(U) Because most equipment units are required to meet electromagnetic compatibility standards such as MIL-STD-461 to ensure that the units will tolerate system noise environments and will not contaminate these environments, it has been postulated that adding an EMP requirement to these existing standards would be a practical way to incorporate EMP protection into system development. The primary advantage claimed for this allocation is that the EMP requirements can be integrated into the normal procurement and qualification routine with minimum added cost.

(U) However, if all the EMP protection is provided by the units and none is required at the system level (as suggested in Fig. 9 by the dashed border of the system and the bold border of the units), the units would be required to withstand very large currents and voltages that can be induced on interconnecting cables, as well as the unattenuated incident EMP fields. In addition, it must be determined that none of

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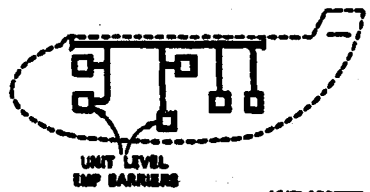
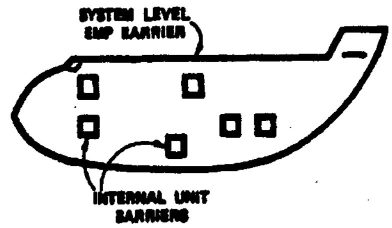


Figure 9. (U) All EMP protection at internal units.



the system-level structure outside the units is essential to the mission (that is, is required to survive the EMP), since none of this structure is helped by the unit EMP specifications. It must also be determined that no EMP interaction with system structure outside the units can cause the units or the system to malfunction.

(U) Because of these limitations, this allocation has never been implemented in a complex military system. In all cases where "box hardening" has been used, the system-level structure has been credited with providing some (often 40 or 50 dB) reduction in the EMP stresses so that the requirements on the units were considerably less severe than they are in the single unit-level barrier allocation. (Allocation in which the protection is distributed between the system level and the units are discussed below.) However, this approach is useful for single-unit systems that have no system-level structure, and it is used for lightning protection of remote telephone cable repeaters, microwave repeaters, and so forth.

Distributed Hardening: Distributed Stress

(U) There are two ways of distributing the protection between the two natural barriers in the system. The important difference lies in whether or not the EMP induces the dominant stress inside the system-level barrier. The allocation that lets the EMP induce the largest stress inside the system-level barrier, as illustrated in Fig. 10, is called the "distributed-stress" allocation. In this allocation, both the system-level barrier and the unit-level barriers have specific EMP requirements imposed on them.

(U) The distributed-stress allocation is used primarily in retrofit hardening, where little system-level structure is available to develop into a system-level barrier and where the cost of installing a system shield is prohibitive. Thus, its main strength is that it allows some hardening to be provided to existing systems

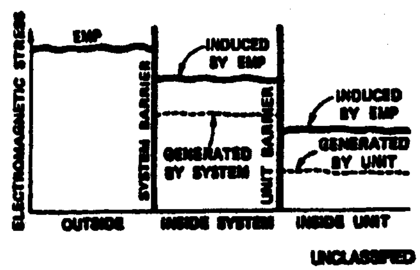


Figure 10. (U) Distributed hardening with EMP-induced stress dominant.

that do not have sufficient system-level metal to form an EMP barrier.

(U) The main shortcoming of distributed-stress allocation is that it is difficult to determine the effectiveness of the protection because of the number of circuits, states, and modes, as discussed above. In particular, because the EMP-induced stresses are dominant inside the system, the system interior response to the EMP is important, and furthermore, it depends on the configuration of the interior structure (cabling, plumbing, and other metal). Changes in the interior may affect the EMP stress inside the system; hence rigorous configuration control is required to maintain hardness. In addition, because the units themselves have specific EMP requirements, a special inventory of these EMP-treated units must be stocked to support the maintenance of hardness, and special care is required to avoid having standard units substituted for the EMP-treated units. Finally, there is concern that the sensitive interior circuits are expected to tolerate a greater wartime EMP stress than they are ever exposed to in peacetime.

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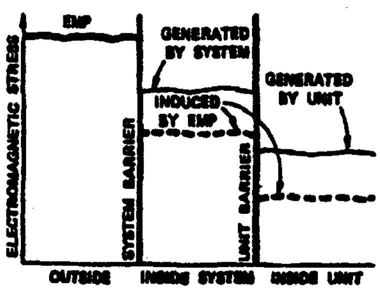

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Figure 11. (U) Distributed hardening with operating stresses dominant.

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Distributed Hardening: Subordinate Stress

(U) The allocation that lets the normal operating system induce the largest stresses inside the system-level barrier, as shown in Fig. 11, is called the "subordinate-stress" allocation. In this distribution of protection, the units are required to tolerate the normal peacetime stresses inside the system, and the system-level barrier is required to reduce the EMP-induced stresses inside the barrier to less than the peacetime stresses.

(U) The subordinate-stress allocation is similar to the single system-level barrier discussed above, but it is presumed that the units can tolerate the normal peacetime stresses. Like the single system barrier, it places no specific EMP requirements on the interior equipment, because the EMP is not the dominant stress on the units or other interior structure. Nevertheless, the protection is distributed between the two barriers; the amount allocated to each barrier depends on the level of normal system operating stress. If the system operating stress is very large, a large fraction of the protection must be provided at the units; if the operating stress is small, most of the protection must be allocated to the system barrier.

(U) This distribution of protection has all the advantages of the single system-level barrier. In addition, it takes advantage of the known tolerance of the units for the normal operating environment in the system.

(U) One feature of the subordinate-stress allocation that may be viewed as a disadvantage is that implementation and maintenance requires specification and control of the normal peacetime environment. This environment is at present only loosely controlled in most systems through the system EMC specification MIL-E-6051. Other considerations are much the same as for the single system barrier.

Other Considerations

Design for Reliability

(U) One of the unique features of the nuclear EMP, and a major reason for concern about reliability and surveillance of hardening, is that most systems will never be exposed to it during peacetime. Thus, during normal peacetime operation of the system, there is no indication of whether or not the EMP protection is adequate. This lack of feedback on performance produces a strong motivation to design the EMP protection in such a way that the opportunities for malfunction are strictly limited and to provide some kind of monitor or surveillance system to artificially generate feedback on hardness status.

(U) Obviously, the ability to maintain system hardness and to know that the protection is still functioning is influenced by the hardening design. One of the objections to the distributed-stress approach is that the hardening is potentially fragile—it is sensitive to many easily possible compromises of the protection, and it is very difficult to monitor or periodically check all these possibilities for compromise. However, it is also possible to design the single-shield and subordinate-stress hardening in such a way that they are fragile and difficult to monitor.

(U) *Consider, for example*, the two barriers shown in Figs. 12a and 12b. These barriers are topologically identical, but they can be physically quite different. The barrier in Fig. 12b is closed through cable shields, connectors, conduit fittings, and similar elements that are easily broken, damaged, or left loose to compromise the barrier. There are many more opportunities for failure of the complex, somewhat fragile shield of Fig. 12b than there are in the rugged, simple structure represented by Fig. 12a. Thus, it is much more difficult to monitor the complex barrier that is rich in failure possibilities than it is to monitor a simple barrier that has only a few likely failure possibilities.

(U) One alternative to the complex barrier with connectors, conduits, and fittings is to divide the barrier into several independent barriers, as illustrated in Fig. 12c. Unfortunately, this approach complicates, rather than simplifies, the barrier, because each of the interconnecting wires that is inside the barrier in Fig. 12b must penetrate the shield and be supplied with individual barrier elements in Fig. 12c. Usually, using separate barriers (as in Fig. 12c) is advantageous only if communication between the units is by means outside the EMP spectrum (for example, optical or microwave), is multiplexed so that one pair carries the information formerly carried by many pairs, or is by nonelectrical means.

(U) In designing EMP hardening, it is well to remember that the personnel who operate and maintain the systems are unaware of the subtleties of EMP protection. For this reason, the EMP protection should be designed so that inadvertent (but routine and expected) acts of operating and maintenance personnel will not easily compromise the protection. It is also advisable to use interlocks, alarms, and other indicators to warn service personnel when the protection has been breached. Large, critical systems should also incorporate surveillance systems that generate the feedback needed to assure the operators that the protection is functioning properly.

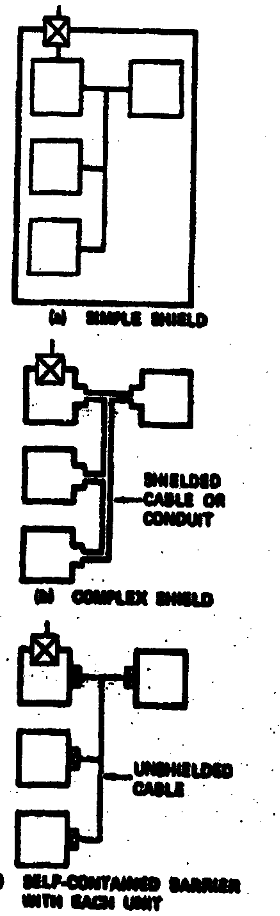

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Figure 12. (U) Variations in EMP-immunity design.

Verifiability

(U) Related to the lack of peacetime experience with EMP is the issue of designing the protection so that it can be verified. Because peacetime operation of the system will provide no information on the EMP protection, a particularly diligent testing effort is required to ensure that the protection will work if it is ever needed. Of course, the simulated EMP stress used to test the system should approximate as nearly as possible the actual EMP, and the system tested should be as nearly identical to the fielded operating system as possible, both in configuration and in operating status and environment. The fewer the extrapolations or other adjustments that are required to account for differences between the test system and an operational system exposed to real EMP, the less likely it is that an important subtlety will be overlooked.

(U) The way in which the EMP protection is designed affects the ease with which it can be evaluated, as shown in the discussions above of the numbers of circuits, states, and modes of operation. Hardening designs that require evaluation of the EMP responses of large numbers of circuits deep in the system for large numbers of system states and modes of excitation are difficult to evaluate.

(U) On the other hand, the protection can be designed to simplify its evaluation. To minimize the uncertainties associated with the absence of peacetime experience with EMP, the protection should be testable. Fortunately, those features described above that make the hardness design more reliable also tend to make it easier to evaluate. Those features that minimize the number of failure possibilities often minimize the number of measurements needed to assess the protection.

(U). Since the EMP that penetrates the metal walls of a shield is usually negligible, simplifying evaluation often implies limiting the number of wires that pass through the shield, limiting the number and size of other openings in the shield, and making the EMP-induced stress subordinate to the operating stresses inside the system.

(U) Surveillance testing that monitors the integrity of the protection in operating systems has the same goal as the design acceptance testing: namely, to determine whether the system is hard. Therefore, a design that is easy to test is also easy to monitor, and a more thorough monitoring system can be devised for a system that has a limited number of failure possibilities.

PROTECTING EXISTING SYSTEMS

(U) While incorporating reliable EMP protection in a new system can be fairly straightforward and economical (particularly when uniform procedures, test standards, and specifications are adopted), a large segment of hardening activity involves upgrading existing systems. Just as there is a large variety of hardening criteria (ranging from very high confidence required in some strategic facilities, to anticipated, but not demonstrated, improvement in nonmilitary systems that are important to the postattack conduct of civil affairs), there is an equally large variation in the amenability of existing systems to EMP protection. Some items, such as telephone coaxial cable repeaters, are designed so that they are easily protected, if indeed they are not already immune to the EMP. Others, such as some of the older communication centers, have little metal structure that can be adapted to EMP protection, and they are so complex electromagnetically that it is difficult to evaluate their responses to high-level transients. Protection approaches for some of these existing, primarily nonstrategic, systems are discussed below.

(U) An orderly EMP protection program begins with an engineering evaluation of the function to be protected, the equipment (and activities) needed to perform the function, the constraints (time, costs, interference with other activities) on the program, and the protective features and devices that may be applicable. The EMP protection must be integrated with other system activities, and the constraints of schedules, system peculiarities, and budgets can be used to determine the most effective, economical, and reliable protective features and devices. However, obtaining accurate and useful information on these four aspects of the system is often tedious.

(U) The function of interest may be the transmission of messages, the performance of selected flight profiles, the delivery of munitions, or the detection, acquisition, identification, and tracking of targets. Although the user can only estimate expected battle situations, he knows that the situation will be complex and that he will need more capability than for routine peacetime activities. Initially, he may also specify that no interruptions can be tolerated; the process of defining realistic and achievable battle capability may involve several iterations among the user, equipment manufacturers, system acquisition managers, and EMP specialists. The protection goals are often a compromise in which tolerable transient effects are defined.

(U) The equipment necessary to perform the function is usually a mix of commercial items, standardized military equipment, and specialized mission equipment. There will be various degrees of operator interaction, control, and reset capabilities. Built-in monitoring and test with some on-hand replacement parts may be an equipment feature. Information on equipment vulnerability thresholds to damage or upset is usually limited. Although more information on thresholds can be obtained by analysis and test, there may not be sufficient time and resources to perform these studies. Furthermore, the potential cost savings of protecting only sensitive items rather than providing overall protection, whether or not all items are sensitive, must be balanced against the cost of analyses and tests to identify and obtain data on the unknown items and to monitor and maintain the protection, once achieved.

(U) Military equipment, subsystems, and systems usually follow an evolutionary sequence that includes concept, preliminary design, final design, prototype production, design validation, serial production, acceptance tests, installation, operational validation, operation, maintenance, repair, and modification. Facilities usually follow a similar evolution from concept to preliminary design, final design, construction, acceptance, beneficial occupancy, equipment installation, user occupancy, operation, maintenance, repairs, and modification. Facilities and equipment may be at considerably different stages of their life cycles when EMP protection is considered. New equipment may be installed in old facilities, and new buildings may have old equipment. Similarly, improved equipment may be retrofit into existing aircraft, while new aircraft may use existing avionics; the long service life of ships almost guarantees that there will be a mixture of new, old, and modified equipment on board. Selection of the most effective and lowest cost EMP protection methods is strongly influenced by the stage in the life of the equipment and the facility or platform, as well as its initial design. Finding space for protective device installation in accessible locations is more difficult after aircraft equipment packaging and placement is far along. Installing a complete building shield may be a major refurbishment program for existing unshielded buildings; on the other hand, systems packaged in all-metal vans or vehicles may be economically protected by developing the existing metal into an EMP barrier.

(U) These variables are not listed to intimidate the reader, but rather to show that EMP protection is as complex as any other aspect of system capabilities and that it faces the same constraints of limited budgets, tight schedules, and interfaces with other system elements. In addition, EMP protection has a few unique considerations. The major unique aspect mentioned earlier is that faults in an EMP protection system are not manifested in normal daily operation. Discovery of faults requires an active maintenance and surveillance effort. A second unique aspect is the inability to test the system in the nuclear environment or to simulate full-scale, threat-level fields for tests on large, complex facilities or systems. Validation requires careful use of available simulation capabilities, combined with analyses, to obtain adequate representations of threat-level response. A third unique aspect at present is the relative newness of some protective devices; data on long-term stability and reliability are insufficient to permit accurate predictions of spare parts requirements or the necessary frequency of surveillance actions. This increases the need for stringent parts control and active monitoring of surveillance and maintenance programs.

CONCLUSIONS

(U) Because the electromagnetic pulse is never experienced in a peacetime environment, but is certain to be experienced in a nuclear engagement, the protection of systems from the effects of the EMP poses some unique problems. Most other electromagnetic effects are more likely to be experienced during peacetime than in war, so that flaws in the protection design are discovered under prebattle circumstances; and indeed, some improvements are almost always needed. To avoid the untenable situation of discovering EMP problems under battle conditions, much effort has gone into developing EMP protection procedures that can be evaluated and maintained with some confidence even though the system is never exposed to the actual EMP.

(U) The key to providing such protection is a system-level EMP barrier that prevents the EMP-induced stress from being the dominant stress inside a system with large numbers of circuits, states, and modes of excitation. In addition, the EMP barrier must be designed to minimize the possibilities for failure; this usually requires some appreciation for human frailties, as well as a good understanding of electromagnetic theory.

(U) However, EMP hardening is also often incorporated into existing tactical or other nonstrategic facilities or systems. Since each such retrofit program has many unique features, as well as unique constraints of schedules, costs, and operating restrictions, no single, universal solution can provide the best EMP protection for existing systems and facilities. The variety of protective measures and protective devices now available permits flexibility in developing EMP protection systems, so solutions can be found for almost any situation of interest. A considerable body of experience exists as guidance in selecting candidate protection methods for potential applications.

(U) In many airborne and marine systems, a major component of the barrier—the shield—already exists in the form of the metal skin or hull. However, in conventional aircraft and ships, this shield is penetrated by many openings, wires, cables, and so forth. These penetrations must be eliminated or the shield must be extended to enclose the exposed wires and cables. In new systems, the added weight and cost of such protection should be nominal; in existing aircraft and ships, the major cost is in designing and installing modifications that provide protection and are also compatible with the ship or airframe. Many aircraft require some additional weight, because the airframe was not originally designed as a shield.

(U) Systems that do not have the rudiments of a system-level shield are much more difficult to protect. The cost and disruption of installing a shield after the system is installed and operating are often untenable. Achieving reliable and demonstrable hardening without a shield is difficult. In new systems, however, an adequate EMP barrier can be incorporated into the design for a small percentage of the system cost; as the technology matures, this cost will probably decrease. Incorporation of the EMP protection will probably also improve the system's tolerance for lightning, power line transients, electronic countermeasures, and other external threats.