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AEP-41

Volume 5

NATO IMPLEMENTATION OF UNIFIED PROTECTION AGAINST ELECTROMAGNETIC ENVIRONMENTAL EFFECTS (UE^3)

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NATO LETTER OF PROMULGATION

13 October 2014

1. The enclosed Allied Engineering Publication AEP-41 Edition A NATO IMPLEMENTATION ON UNIFIED PROTECTION AGAINST ELECTROMAGNETIC ENVIRONMENTAL EFFECTS (UE^3), Volume 5 on UNIFIED PROTECTION AND HARDENING AGAINST E3, which has been approved by the nations in the NAAG/JCBRND-CDG, is promulgated herewith. The recommendation of nations to use this publication is recorded in STANREC 4567 Edition 1.

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AEP 41, VOLUME V

UNIFIED ELECTROMAGNETIC ENVIRONMENTAL EFFECTS (UE^3) PHILOSOPHY AND METHODOLOGY

2.0 AEP-41, EXECUTIVE SUMMARY

There is a general consensus for an unified approach to the protection and hardening of all NATO military platforms, systems and equipments (hardware) against Electromagnetic Environmental Effects (E^3) caused by the plethora of Electromagnetic Environments (EMEs) that these platforms, systems and equipments are subjected to during their deployment life. These E^3 can adversely impact the operational capability of this military hardware resulting in their inability to accomplish their mission or even putting the crew's safety at risk. The EMEs are generated by natural, operational and hostile sources. Additionally, today's complex military operational environment is characterized by: multi-national operations, increasingly crowded EM spectrum coupled with a reduction of bandwidth allocated for exclusive military use, military hardware whose mission performance is dependent on electronics, and hardware that is increasingly dependent on more energy sensitive Non-Developmental Items (NDIs) and Commercial-Off-The-Shelf (COTS) electronic components. Traditional hardening against the total battlespace EMEs has been accomplished by considering each EME individually and serially. The Conference of National Armaments Directors (CNAD) recognized the need for a Unified E^3 (UE^3) protection policy, and directed the development of an Allied Engineering Publication (AEP) 41 and an associated Standardization Agreement (STANAG) 4567 to describe and define this policy. The proposed UE^3 protection approach can be applied to all six Operational Categories (OCs) of NATO military hardware. These six OCs are:

OC1 Land Mobile Systems
OC2 Static Land Systems
OC3 Space Systems
OC4 Sea Platforms
OC5 Air Platforms
OC6 Command, Control and Information Systems

The CNAD approved the following seven AEP 41 volumes to detail the different functional areas required to achieve, produce and sustain affordable UE^3 protection and survivability:

a) Volume I, Unified Electromagnetic Environmental Effects (UE^3) Protection, Philosophy and Methodology
b) Volume II, Electromagnetic (EM) Environments (EMEs), E^3, and Operational Categories

c) Volume III, Electromagnetic Coupling
d) Volume IV, Susceptibility of Platforms, Systems and Equipment to E^3
e) Volume V, Unified Hardening and Protection Against E^3
f) Volume VI, Testing and Validation of E^3 Protection
g) Volume VII, Hardness and Sustainment Assurance, and Surveillance Test

The basic philosophy is to provide a User-controlled, performance-based approach to developing cost effective, verifiable, producible, maintainable and sustainable UE^3 protection for NATO military hardware. The methodology for implementing UE^3 protection to all types of military hardware is based on use of an EM barrier protection concept. In addition, this methodology is inherently accommodating and flexible for future growth and changes, and for sustaining EM hardness against degradations resulting from usage, age, maintenance and repairs, changes and additions, and ambient environments. This AEP uses extensively the UE^3 Protection Philosophy and Methodology documented in QSTAG 1051.

2.1 INTRODUCTION FOR AEP 41

2.1.1 Balanced E^3 Protection. This AEP describes an approach for achieving adequate, affordable and balanced UE^3 protection and survivability in the battlespace for all classes of NATO military platforms, systems, and equipments (all three defined as hardware) of the six operational categories. Balance is achieved between several factors. First, the protection design is balanced for unified coverage of the EME stresses encountered during hardware operations. Second, a balance is achieved between the protection provided and hardware cost and operational impact. Third, the User can balance the level of protection against risk of operational degradation in the presence battlespace EMEs. The philosophy embodied in AEP 41 does not mandate design solutions; but instead, provides a performance-based methodology that allows the User the flexibility for deriving the final UE^3 protection design to meet performance requirements.

2.1.2 E^3 Protection Needs. Adequate E^3 protection of electronic/electrical military hardware is essential since such hardware must operate during and after exposure to increasingly severe, complex and changing EMEs that can potentially impact crew safety as well as degrade or even destroy mission essential performance capabilities. Potential battlespace EMEs are listed in Table 1. Meeting the E^3 protection requirement has become more difficult due to the post-cold war policy of deploying NATO coalition forces (even combined with UN forces) consisting of military hardware hardened to different E^3 levels into many different areas each with its own set of EME threats. This disparity in E^3 hardening, combined with different national policies on E^3 survivability sustainment, has resulted in deployment of NATO hardware with widely varying E^3 survivability/vulnerability levels. Thus, the deployed force has EM compatibility (EMC) problems. In addition, most of the hardware was developed in the cold war. Post-cold war policy of most NATO countries is to extent the operational life of their deployed hardware by a factor of two or more. This lifetime extension combined with rapidly advancing technology and increasing obsolescence has become the reason for multiple modernization cycles (was one, now eight-to-ten) and the increasing use of COTS/NDIs and advanced technologies both of which tend to have lower energy upset and damage thresholds. These new impacting factors are in addition to the traditional ones (worsen by the longer deployment lifespan) that can degrade E^3 survivability such as ambient environments, corrosion, aging, usage, and repeated maintenance and repairs. Thus, the combination of these new and old factors has greatly increased the difficulty of sustaining E^3 survivable hardware.

Table 1. Characteristics of Battlespace EMEs.

Externally Generated Electromagnetic Environments			
Environment	**Type**	**Waveform**	**Propagation ***
Near Strike Lightning (NSL)	Natural	Pulse	Radiated and Conducted
Direct Strike Lightning (DSL)	Natural	Pulse	Conducted
High Altitude Electromagnetic Pulse (HEMP) E1, E2, E3	Hostile	Pulse	Radiated and Conducted
Source Region EMP (SREMP)	Hostile	Pulse	Radiated and Conducted
Non-Nuclear EMP (N^2 EMP)	Hostile	Pulse, Damped Sine	Radiated
Electromagnetic Emissions	Electronic Operation	Pulse, CW and Modulated CW	Radiated and Conducted
High Intensity Radiated Field (HIRF)	Electronic Operation	CW Pulsed, CW and Modulated CW	Radiated
Electronic Counter Measures (ECM)	Hostile	CW and Modulated CW	Radiated
High Power Microwave (HPM)	Hostile	CW Pulsed, CW and Modulated CW, single or multiple Bursts of CW	
Ultra-Wideband (UWB)	Hostile	Pulse, single or multiple	Radiated and Conducted
Precipitation- Static (P-Static)	Natural	Pulse	Conducted
Electrostatic Discharge (ESD)	Natural	Pulse	Radiated and Conducted
System Generated EMP (SGEMP) External	Hostile	Pulse	Radiated and Conducted
Dispersed EMP (DEMP)	Hostile	Pulse	Radiated and Conducted

*Propagation is the method by which energy arrives to the victim from the source

Internally Generated Electromagnetic Environments			
Enviroment	**Type**	**Waveform**	**Propagation ***
Electromagnetic Emissions	Electronic Operation	Pulse, CW and Modulated CW	Radiated and Conducted
Electrostatic Discharge (ESD)	Natural	Pulse	Radiated and Conducted
SGEMP – Internal (Box and Cable)	Hostile	Pulse	Radiated and Conducted

*Propagation is the method by which energy arrives to the victim from the source

2.1.3. Methodology. The method of achieving UE^3 protection and survivability is through the use of EM barrier(s) plus special protective measures to protect Mission and Safety Critical Electronics (MSCEs). An EM protection barrier consists of two elements: one or more EM shields, and the necessary electrical and mechanical penetrations through the shield(s). To maintain the barrier effectiveness, penetration protection devices must be provided for all penetrations in the EM shield. Figure 1 illustrates the EM barrier protection concept applied to a multi-element system. (Note that this concept can be effectively applied to military hardware that has effectively no shield e.g., modern aircraft (OC5).) This protection concept is familiar to digital, circuit, integration and system designers; and, does not require the development of new design practices. The illustrated example employs multiple closed metallic EM barrier topologies to reduce the externally and internally generated EME stresses (conducted and radiated) to residual stress levels consistent with acceptable operation of the protected MSCEs. Choosing the acceptable operational levels and, in turn, the EM barrier performance requirements involves a process of balancing the externally and internally generated EME stresses, the MSCEs immunities, and the margin selected to control risk. The engineering trade studies necessary to achieve this balance are through the allocation process, illustrated in Fig 2, which is usually iterative and serves basically as a risk management tool. If the EM barrier concept is properly designed and implemented into military hardware, UE^3 protection and survivability can be achieved that is affordable and producible as well as verifiable, maintainable and sustainable throughout the hardware's operational life. Additionally, an integral and essential part of this methodology is testing, which is conducted throughout all four of the acquisition life-cycle phases to insure that the EM protection design is: adequate and complete during concept and engineering development, properly implemented during production, and properly maintained and sustained during deployment. Furthermore, the EM barrier protection concept facilitates unified testing by focusing on the barrier rather than individual E^3. Since this methodology can create benign internal EME stresses to which the MSCEs must survive, the EM barrier facilitates Diminishing Manufacturing Sources and Material Shortages (DMSMS) and technology insertions, especially COTS/NDIs, and upgrades/enhancements.

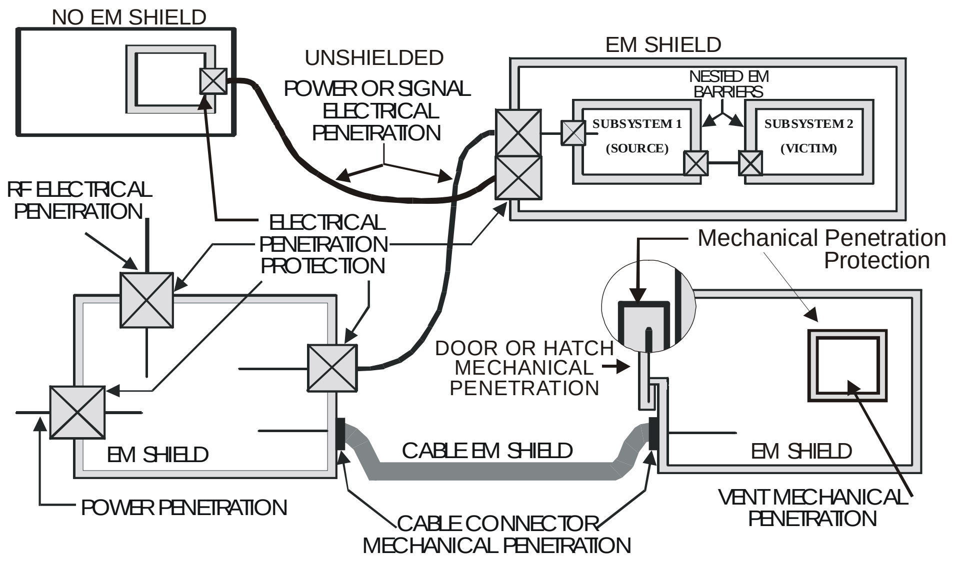


Figure 1. Multiple Barrier Topology Design

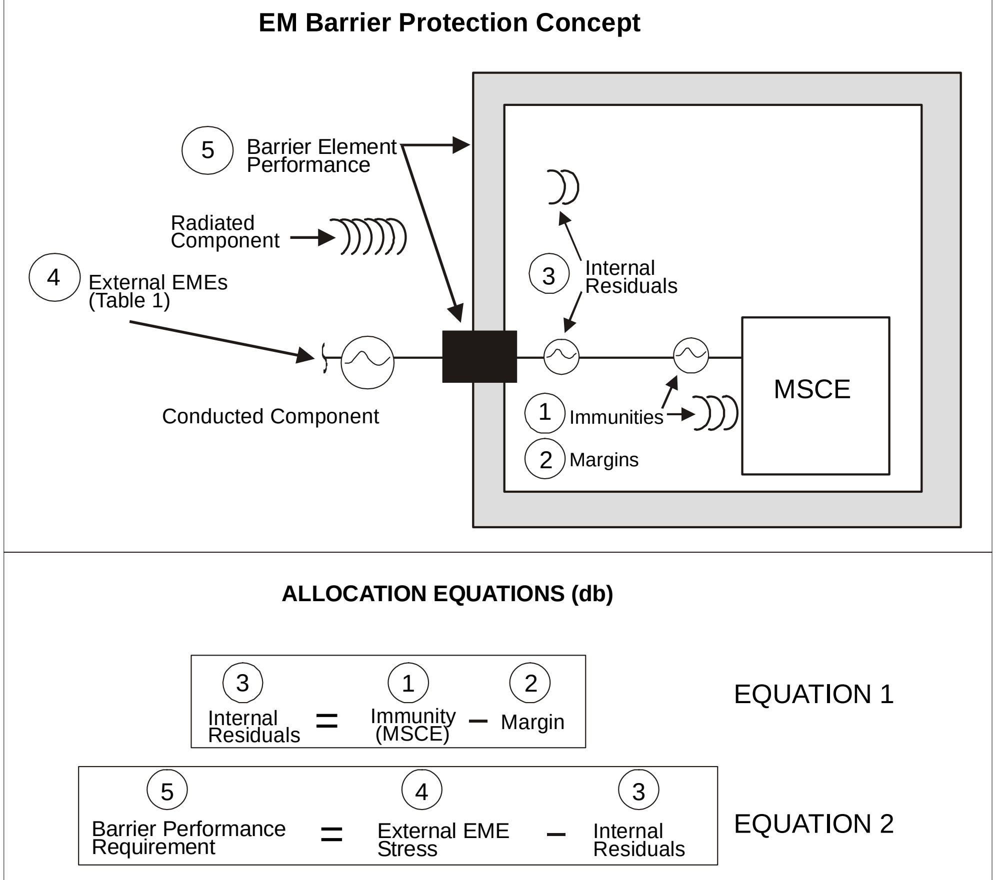


Figure 2. EM Barrier Protection Concept Keyed to Allocation Equations.

2.2 SCOPE FOR AEP-41

The general scope of this AEP is to document how affordable for all UE^3 survivability can be achieved, verified, produced and sustained for all six categories of NATO hardware using the EM barrier protection concept. This scope of work will be accomplished in the following seven volumes.

2.2.1. Volume I. This volume provides the philosophy and methodology for achieving affordable UE^3 protection and survivability through the use of the EM barrier protection concept. A discussion of how to apply the EM barrier protection methodology to achieve UE^3 survivability that is affordable, verifiable, producible and sustainable in todays and the future battlespace is provided.

2.2.2. Volume II. This volume provides the typical requirements for and defines and discusses the potential battlespace EMEs listed in Table 1 that military hardware must be protected against in order to be E^3 survivable in the battlespace. These EMEs interact with military hardware causing E^3, which are defined and discussed. Furthermore, military hardware (platforms, systems and equipments) of the six operational categories is discussed.

2.2.3. Volume III. This volume provides detailed discussion of E^3 coupling for the various classes of military platforms, systems and equipments defined in Vol. II. Understanding E^3 coupling is critical because the EM barrier is basically an E^3 management tool to insure that the resultant residual levels from the EME generated stresses are lower than the MSCE immunity levels by a realistic margin. (Margin depends on mission criticality of hardware and permissible risk; therefore, margin is usually 15-20 dB, which is adequate only if combined with a thorough life-cycle program.)

2.2.4. Volume IV. This volume discusses E^3 susceptibilities common to the six categories of NATO military hardware defined in Vol. II. How these E^3 susceptibilities occur, what they are, and how they affect these various hardware classes in the battlespace is discussed.

2.2.5. Volume V. This volume describes how to apply the EM barrier protection concept to achieve UE^3 protection and survivability against the E^3 susceptibilities described in Vol. IV resulting from the E^3 coupling described in Vol. III for the six operational categories of NATO hardware defined in Vol. II. Volume V also discusses why E^3 protection must be included early into the design of military hardware in order to be affordable, producible, sustainable as well as accommodating to insertions of DMSMS solutions and COTS/NDIs.

2.2.6 Volume VI. This volume discusses test and validation. A crucial part of achieving, producing and sustaining UE^3 survivability is a series of E^3 tests that must be performed during all phases of the hardware's life-cycle and tailored to the requirements of the hardware. The basic test types are: engineering development to support the design activities, acceptance (MSCE equipment immunity (both radiated and conducted) and barrier performance (shielding effectiveness and penetration protection devices)), final design validation, production compliance (under Hardness Assurance (HA)), deployment compliance (under Sustainment Assurance (SA)), and Surveillance Test (ST). Both HA and SA includes engineering-type tests and analysis, as necessary, to evaluate and validate that configuration, MSCE, and material changes do not degrade the E^3 survivability level of the hardware by increasing risk to unacceptable levels.

2.2.7 Volume VII. This volume discusses hardness and sustainment assurance, and surveillance test. The test and validation aspects of design, engineering development, and hardness assurance are presented in Vol. VI and will be briefly covered in Vol. VII for completeness. Consequently, Vol. VII focuses on sustainment assurance and surveillance test. The objective of a hardness and sustainment assurance program is to establish technical and management activities to ensure that UE^3 survivability achieved and verified during the Engineering Development Phase is not only produced, but, is also preserved throughout the hardware's Deployment Phase or its operational life. Also discussed are methods and guidelines on how to accommodate material changes, technology/DMSMS insertions and associated circuit additions, MSCEs upgrades and modernizations without degrading E^3 survivability to unacceptable risk levels during deployment. Finally, surveillance tests (and analysis) to periodically validate adequacy of both hardness and sustainment assurance programs are discussed.

2.3 Requirements

Military hardware of the six operational categories must be electromagnetically compatible as well as survivable to a myriad of changing EMEs in the battlespace; and, this compatibility and survivability must be readily achievable and affordable as well as producible, maintainable and sustainable throughout the hardware's life-cycle. EMC, survivability, and EME requirements are provided in Section 4 of Volume II.

The barrier performance requirements critical to achieving affordable, producible and sustainable UE^3 protection for NATO military hardware of the six operational categories are discussed in section 4.0 of Volumes I, III and V. The E^3 performance objectives are established from the mission needs, E^3 protection criteria and concepts, and the selected E^3 survivability options (may require combinations of UE^3 barrier protection with alternate and/or special protective methods to achieve survivability). The performance objectives consist of: need to protect against specific EMEs, level of protection required, amount of allowable risk associated with the protection and, as needed, limits on hardware impacts related to E^3 protection. See Volume I, Figure 12 for illustration and para.4.2.2 for discussion. It is important that the E^3 performance objectives be clearly defined early in a program, since they drive performance specifications as well as all subsequent UE^3 protection design and engineering and acceptance test activities, affordability, producibility, sustainability, and flexibility of design.

3.0 AEP - 41, VOLUME V, EXECUTIVE SUMMARY

3.1 INTRODUCTION TO VOLUME V OF AEP - 41

Based on the philosophy of AEP – 41, guidance is needed for UE^3 Protection (UE^3P) of all military equipments, platforms and systems against EMEs (see Section 2.2, Table 1) that they may encounter during there full service life. The method defined to achieve UE^3P is based on the balanced use of the classical EM barrier protection concept and a unified coverage of the EMEs (see Vol. I, Para 4.2.2.3). The EM barrier is a generic term covering all methods of EM protection. Usually the barrier consists of one or more electromagnetic shields and controlled mechanical and electrical penetrations through the shields. However, it also covers filters, lossy materials, circuits and software design measures. The required protection and hardening measures are based on the Unified Barrier Performance Requirements (UBPRs) (see Vol. 1 Para 4.2.3.4.3) which must take into consideration both linear and non-linear effects (see Vol. I, Section 4; Vol. V and Section 4.3 and 4.4).

3.2 THE AIM OF VOLUME V

Volume V serves as guideline to achieve UE^3P to reduce the costs of development, construction and sustainment by the exclusion of supplementary, conflicting and redundant measures. The degree to which elements of the EM barrier(s) treat multiple E^3 is a measure of the degree of unification. For example, a solid EM shield of an enclosure with no apertures is a barrier, which can protect against all E^3. For this case, the degree of unification would have a numeric value equal to the number of all EM environments, which are required for the system. If there were three EM environments required, like NSL, HEMP and HIRF, then the degree of unification would have the numeric value of three. The aim is to achieve UE^3P with the maximum degree of unification by applying the barrier protection concept in consideration of E^3 coupling described in Vol. III and E^3 susceptibilities described in Vol. IV.

3.3 SCOPE OF VOLUME V

3.3.1 Document Inclusions and Exclusions. This volume provides details on the realisation of UE^3P against battlespace and peacetime EMEs. It is based on the foregoing Volumes I to IV, which define the scope and the preconditions. The procedures of the experimental validation of UE^3P are described in Volume VI.

3.3.2 Layout of Document. The Executive Summary of AEP - 41 is part of all volumes and allows the reader to get a quick overview about the intention and the methodology of this AEP. Thereafter, the special intentions of Vol. V are presented in Section 4.0, where the procedures and means are described to realise UE^3P. Shown in Section 4.0 is how UE^3P is based on classical EMC protection measures and how UE^3P is inserted into the life-cycle concept of defence materiel. Finally, the summary and the conclusion terminate Vol. V. Special problems and references are presented in the annex.

4.0 OBTAINING OPTIMUM UNIFIED PROTECTION AND HARDENING

4.1 PRECONDITIONS FOR THE REALISATION OF UNIFIED E^3 PROTECTION AND HARDENING

Unified E^3 protection and hardening measures are based on a complex analysis of all work areas involved in EM protection. In the first step of the analysis, one can investigate the coupling paths of the various EM fields (see Vol. III) without considering protection measures (see Vol. V) and the resulting EM stresses (see Vol. IV) on the electronic components to estimate the necessary degree of the UE^3P measures. This is related to the EM stresses on the Mission and Safety Critical Electronics (MSCEs), their immunity/susceptibility levels and the desired confidence level (see Vol. I, Para 4.2.3.). Then in a second step, balanced protection and hardening can be achieved both for the frequency and for the time domain EM stresses, since the UBPRs of all possible protection measures are known or can be determined and in the same way the quality parameters of the hardening measures are available.

4.1.1 Unified E^3 and Associated Risks. There are associated risks if the protection and hardening of systems based on the UE^3 philosophy is not applied correctly. The reduction of undesired redundancies increases the importance of each UBPR, of each barrier and of each qualification test with respect to required hardness of the system. Therefore, a comprehensive analysis of UE^3P and comprehensive qualification management are necessary (see Section 4.2 in this Volume and Volume III).

4.1.2 Systems and Equipment Dimensions, Topology and Linkage

The UE^3P concept has to consider the size, the EM topology, materials (conductive and non-conductive), and the linkage of systems or equipments. The size is an important criterion for different aspects: such as resonances that depend on size of the hardware (electrically small/large), and magnitudes of Box-Internal SGEMP (IEMP) EM fields and consequent induced cable currents increase in proportion to the shelter dimensions presented to the incident gamma flux [1]. The right EM topology can reduce cross-talking, which reduces the costs of protection measures. The material, its conductivity / dielectric constant, its distribution in an enclosure, affects the quality factor Q of a cavity. Finally, Q, the sizes, the topology and the kind of EM excitation determine the possible amplitude of the induced stress. To achieve balanced protection and hardening of the considered platform/system, it is necessary to know the dependencies on other physically, electronically and/or RF linked systems, subsystems and equipments, which can be exposed to the same EMEs. These linked platform/system elements (systems, subsystems and equipments) have to be evaluated too, to avoid a weak link in the chain. That can result in individual problems or cause interoperability or network-centric problems. Future forces will operate as a system-of-systems unit consisting of many different systems connected primarily by RF links. In principle each system can be divided into a number of subsystems or equipments connected to each other in a certain way of order. The UE^3P concept should start early in the system life-cycle. Then it may still possible to change this order of subsystems and equipments to achieve an economical solution of balanced protection.

4.1.3 E^3 Coupling The coupling of the EMEs into the platform/system is described in Vol. III. Since the coupling model has to reflect the UE^3P concept and additionally the platform/system can be divided into subsystems and equipments, the determination of the protection measures and their locations can be very complex. The intention of this AEP is to establish a well-defined UE^3P concept. This is possible if a barrier protection concept is developed correctly with well defined interaction zones. The big advantages of this concept are; firstly, that the quality of the interaction zones can be estimated by theory in advance (see Vol. III) and finally can be qualified by well defined tests (see Vol. VI), secondly, it is possible to qualify subsystems and equipments during the last two life-cycle phases of the hardware (manufacturing, modernization/upgrading, and deployment phases).

4.1.4 MSCEs Susceptibility to E^3. The UE^3P concept can be concentrated on MSCEs to reduce costs. The susceptibility levels of MSCEs have to be determined by engineering tests (see Vol. IV) as a function of all relevant stress parameters (e.g., frequency and time domain, radiated and conducted, and degradation of hardening and protection device/component). In this way it is possible to determine well defined safety margins and the degree of the barrier protection levels. The whole system can fulfil its mission in the EMEs of a battlespace if the most sensitive class of MSCE is hard against the required EMEs.

4.2 DETERMINATION OF STRESS TRANSFER FUNCTIONS AND WAVEFORM NORMS

The UE^3P concept is based on the barrier concept, which provides well defined interaction zones when established correctly. Only then analysis of E^3 coupling (see Vol. III) through these interaction zones is feasible. The analysis leads to Stress Transfer Functions (STFs), which can be linked to the susceptibility levels of MSCEs, and this finally allows an optimisation of the UE^3P concept. The STF is a function, which can describe the E^3-coupling phenomena even if Non-Linear Effects (NLE) occur. NLE, for example, can be caused by sparking, diodes, dispersion, and melting. These effects lead to the problem that there is no longer a simple linear relationship between excitation and response function. Therefore, the response function has to be determined directly in the time domain (e.g., use of a transient digitiser or use of theoretical calculations/considerations), and not in the frequency domain. If NLE occur the STF can be expressed by relating the excitation and the response function using waveform norms (N_k, k=1…7; see Vol. I Para 4.2.3.5 and Vol. III Para 4.9.3). To determine UBPRs the necessary immunity levels can be related only to one waveform norm. Normally, this is the Peak Amplitude Norm, because every effect depends at least on the amplitude of the stress. In cases where the relation between waveform norms and EM effects is known the immunity levels could be related to more than one waveform norm. This could optimise the use of protection measures (e.g., if the effect is limited to the Peak Derivative Norm, the protection measures can focus on the reduction of the peak derivatives of the waveform, which does not have to be identical with the Peak Amplitude Norm).

4.2.1 Stress Transfer Functions of the Relevant Coupling Paths

There exist two types of relevant coupling paths. One is the penetration of radiated EM fields through space or shields, and second is the penetration of currents and voltages on a conductor or through protective devices, like filters or non-linear elements. The UE^{3}P concept should lead ideally to coupling paths with negligible EM interaction between radiated and conducted coupling. This can be achieved by the barrier concept, which can lead to topological zones. In this case, STF of radiated and conducted stresses can be treat separately, which simplifies the unification process. If an EM interaction between radiated and conducted coupling cannot be avoided, the region where the interaction occurs should be treated like an additional topological zone. Each topological zone is exposed to an EME that is generated by the neighbouring zones. The transfer of stresses between neighbouring zones can be quantified by STFs. The STFs describe the quality of the protection measured against radiated and conducted stresses of the applied EMEs.

4.2.1.1 Radiated Stress The primary coupling process of the battlespace EMEs (see Table 1) is radiated coupling on the exterior equipment cables and/or conductive surfaces. Exceptions are DSL, P-Static and ESD. Examples of radiated coupling are described in Vol. III, Sections 4.3 to 4.6. There, the coupling to vertical or horizontal conductors, to Printed Circuit Boards (PCBs) and MSCE components, and the coupling into shields and to its interior cables, are discussed in detail. The result of radiated coupling is a current or voltage wave coupled onto a conducting material, like the shield of an enclosure or cable. These current or voltage waves, serve as new EME source for radiated stress or for conducted stress to equipment inside the enclosure and are the primary sources for the effects on MSCEs (see Figure. 2, Section 2.1.3).

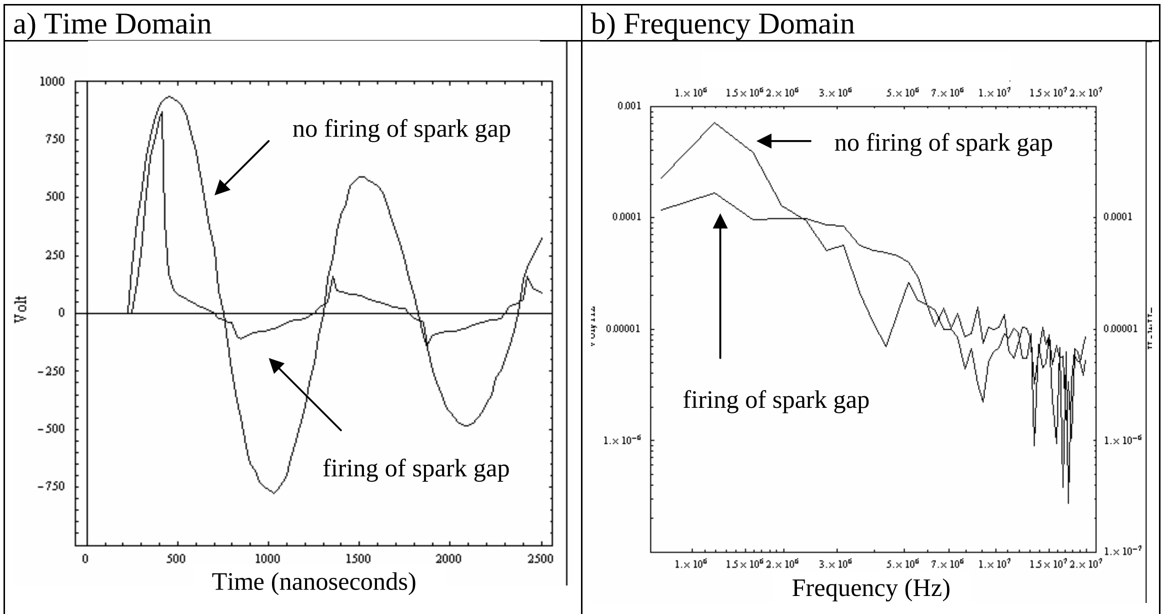
4.2.1.2 Conducted Stress The induced current and voltage waves on shields, cables, wires, or on PCBs are the direct carrier of the conducted stress to internal MSCEs. The measure of the coupling to conducted material and the measure of the stress to MSCEs, have to be related to waveform norms of the external and internal EMEs. These waveform norms lead to the relevant STF.

4.2.2 Waveform Norms and Unified Protection Waveform norms are useful in the unification process. These Norms can serve as tools to compare the stress content of external and internal EMEs, if Norms and EM effects can be correlated (see Table 2, or Volume III). With this comparison, the maximum stress content of the relevant EMEs can be determined. This is defined as Unified Stress (US). That analysis can disclose the characteristics of battlespace EMEs with respect to necessary protection, e.g., their dissimilarities and similarities. Each disclosed dissimilarity need, of course, special attention and can lead to special protection measures. Therefore, this analysis is important to achieve optimum UE^{3}P. The following sections describe potential applications of important waveform norms and their correlation to potential effects. These applications are based on engineering experiences. The main goal of protection measures is to reduce the values of the waveform norms (see Para 4.5) for each coupling path.

4.2.2.1 Linear Description and Contribution to Non-Linear Effects

A straight-forward UE^3P topology can lead to well shielded enclosures and well-defined protection measures for conducted stress - that means all cables are protected with shields (therefore, only linear effects must be considered). An example, a good straight-forward EM protection topology is the EMP protection of mobile NATO shelters [Ref 11]. In this case, the quality of the shield protection can be described with <u>linear</u> STFs. Because of the sufficient shielding effectiveness, no sparking occurs in the space between the shield of the enclosure and the measured voltage or current waves on shielded cables. Therefore, EM fields inside the enclosures are related linearly to the external EMEs.

Further, possible sparking is only allowed in non-linear protection elements, which are built in special shielded zones (for example, EMP-vaults or RF enclosures). If the strength of the non-linear residual conducted stress is large, then additional shielding may be required.


a) Time Domain

b) Frequency Domain

Figure 3. Example of a NLE, which Depends <u>on</u> a Threshold Level: Voltage of a Damped Sine (1kV, 1 MHz - MIL-STD 461C), after the Propagation through a 90 Volt Gas Spark Gap – a) Time Domain Measurement, b) Fourier Transform of Measurement

Therefore, the quality of the shielding effectiveness of this protection topology can be described with linear STFs (transfer functions) in the frequency or in the time domain. Furthermore, the EM coupling to screened cables or cables which are connected to linear ports of electronics (in this case, there are no diodes or rectifiers connected to the entrance port) can be described with linear STFs up to stress amplitudes where no NLE occur (see Figure 3). Examples of NLEs, which depend <u>on</u> a threshold level are, sparking, dielectric breakdown, burnout of semiconductors, saturation or rectifying effect, toggling of digital circuits, punch through, metallisation, and thermal failure.

Additionally, there exist NLE that are independent of stress amplitude (see Figure 4). Example of NLEs, which depend not on a threshold level are, e.g., rectifying of the coupled waveform, electromagnetic parameters of material that depends on the frequency of the waveform, and non-linear transmission lines.

If the system reacts in this way, the linear STFs cannot describe the correct response of the system. For this case, time domain calculations/measurements must to be performed.

Of course, the quality of non-linear protection measures for conducted stress, the switch parameters of non-linear protection elements, has to be measured only in the time domain.

The time domain waveforms before and after the NLE occurrence can be analysed by determining their waveform norms. The relations of the waveform norms before and after the NLE occurrence can be useful for characterising the quality of protection measures and are representatives of STFs.

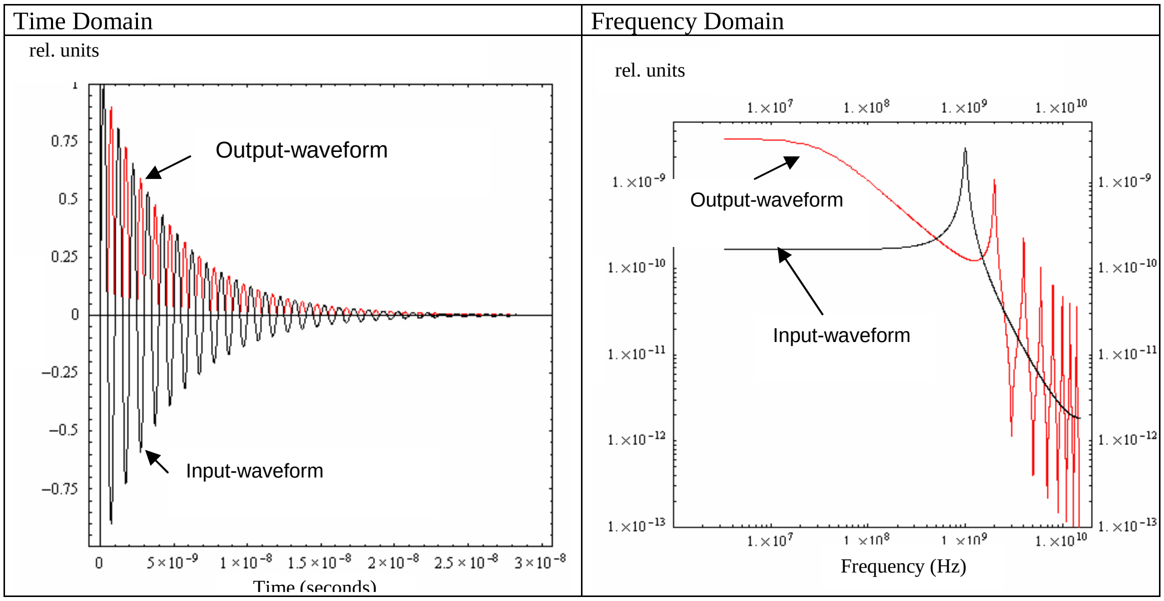


Figure 4. Example of a NLE, which Depends not on a Threshold Level: Input-waveform (Damped Sinus, Q = 15, f = 1 GHz, Peak Amplitude = 1):___ Output-waveform (Rectified Input-Waveform):____

Table 2. Typical Waveform Norms

Waveform Norm Name	Waveform Norm Description	Related Effect on Electronics
Peak Amplitude (N_1)	$N_1 = \left\| f(t) \right\|$	Toggling of digital circuits Dielectric breakdown Punch through
Peak Derivative (N_2)	$N_2 = \left\| {df(t)}/{dt} \right\|_{MAX}$	Mutual coupling Reactive element response Toggling of digital circuits
Peak Impulse (N_3)	$N_3 = \left\| \int_0^t f(x)dx \right\|_{MAX}$	Toggling of digital circuits Dielectric breakdown
Rectified Impulse (N_4)	$N_4 = \int_0^\infty \left\| f(x) \right\| dx$	Toggling of digital circuits Dielectric breakdown Analog circuit drift and latch up
Root Action Integral (N_5)	$N_5 = \left\{ \int_0^\infty \left(\left\| f(x) \right\| \right)^2 dx \right\}^{1/2}$	Thermal failure (junction burnout) Metallisation melt

4.2.2.2 Energy / Power Criteria (Root Action Integral) The energy/power of a waveform coupled into the MSCE is normally a useful measure, because each possible effect needs at least a certain amount of energy or power.

The energy of a stress will be used, if the threshold of an observed effect depends on the energy. In this case, the effect has to occur in a finite time. A specific relaxation time is the important criteria to characterise an energy or power dependent threshold. Examples for relaxation times are, e.g., the time for a junction failure in integrated circuits (can be in the order of 10 ns to 1 μs [7]), and the time for ignition of flammable atmospheres (about 20 μs -100 μs [8]). The energy content of the stress will characterise the threshold if the effect will be initiated for times less than the relaxation time (adiabatic effects). The power of the stress will characterise the threshold if the effect will be initiated for times longer than the relaxation time (quasi-static effect).

The Wunsch-Bell-Model [9] is a well known theoretical model to estimate the junction failure in semiconductors and relates the required burnout energy to the duration of the pulse.

Beside these stress related applications of energy, energy is a useful quantity in coupling theory (see Vol. III, Para. 4.4.2.3, Energy Bounds), because it allows worst case coupling considerations (e.g., estimate the maximum electric or magnetic field strength, or current or voltage amplitudes).

4.2.2.3 Peak Derivative

The peak derivative (peak time rate of change) of the stress is the quantity that is related to coupling of EM fields into loops, apertures, shielded enclosures or into the earth ground.

4.2.2.4 Peak Amplitude

The peak amplitude of the stress (EM field strength, voltage, current) is one of the most important quantities to characterise the stress. This quantity is normally used to define thresholds without knowing the related effects.

4.2.2.5 Peak Time Integrals (Peak Impulse, Rectified Impulse, Root Action Integral)

The peak time integrals are important to characterise the ability of dielectric breakdown and semiconductor damage. See Table 2.

4.2.2.6 Susceptibility Levels for the Unified Stress Quantification

The necessary UE^{3}P measures depend in a high degree on susceptibility or at least on immunity levels of MSCEs. Normally, susceptibility levels of MSCEs will be determined in the allocation process for military hardware, if the hardware is vulnerable against the considered recommended battlespace EMEs. Of course, in this case, EM hardening is required. Otherwise, immunity levels will only be determined to avoid tests with unrealistic high stress amplitudes.
The known susceptibility levels can usually not be applied directly for the US Quantification. The reason is these levels are determined with respect to the existing standards and not to a unified EME. But, indirectly, important information for UE^{3}P can be extracted by comparing the stress of the applied existing standards with the stress of the unified EME. It is possible to compare the amplitudes, frequency band, pulse duration, pulse sequence or generally the waveform norms. The best way to avoid redundancies in UE^{3}P should be to link susceptibility levels only to US.

4.2.2.7 Safety Margins

The Program Manager should define a safety margin, depending on the importance of the system.

With respect to UE^{3}P the question arises, whether it is necessary to add an additional safety margin to the typical one’s, because the UE^3 – method avoid redundancies (see also Para 2.1.3, 2.2.3, 4.3, 4.6, 4.7). An additional margin can lead to system qualification.

4.3 DETERMINATION OF THE REQUIRED PROTECTION AND HARDENING MEASURES

This paragraph will illustrate the correlation of the unified stress with a barrier concept. The barrier concept is based on the system topology and therefore it can be very complex. One possibility to obtain an optimal concept is a step-by-step reduction of the possible barriers up to the necessary limit. Figure 5 illustrates the multiple barriers hypothetically required for the protection of a component as determined by individual consideration of unified stresses. That is, each barrier is unique to the protection for one specific unified stress.

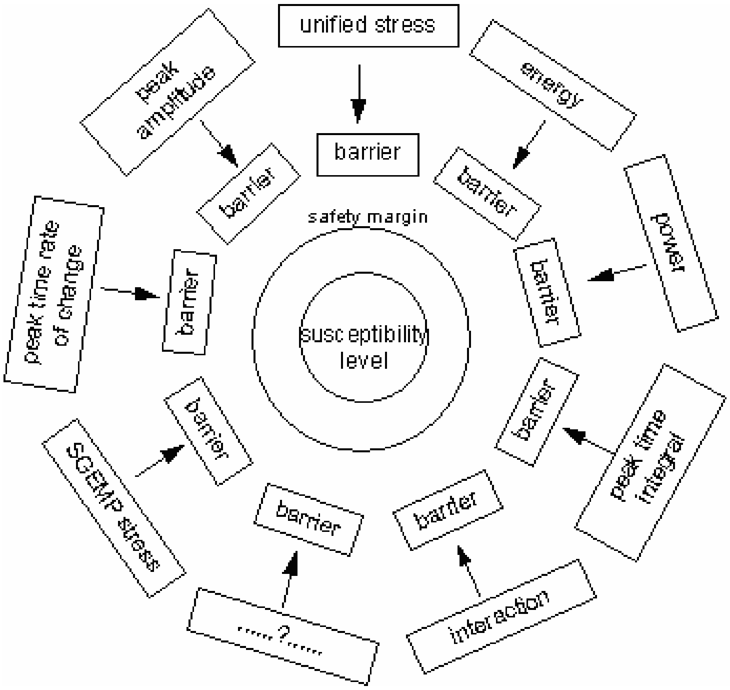


Figure 5. Centric Illustration of the Barrier Concept <u>without</u> Reducing the Number of Barriers by Exploiting all Protection Properties of a Barrier for one EME

In the middle of this illustration, the susceptibility level and the safety margin of a black box is indicated by circles. The black box has to be protected against the external and internal EMEs, listed in Table 1. It can symbolise a complex system, a component of a system or an electronic device of a component. It interacts with its EMEs and is linked to another black box that is needed for its operation. The EMEs are characterised by their unified stress. For each possible coupling path a special barrier is mounted and protects the black box against the stress of its environment, indicated by arrows.

4.4 OPTIMISATION OF THE BARRIER CONCEPT

The barrier concept can be optimised if barriers are used, which have a protection effect against more than one stress parameter (e.g., shield of an enclosure, spark gap). This can in principle lead to the following final solution shown in Figure 6:

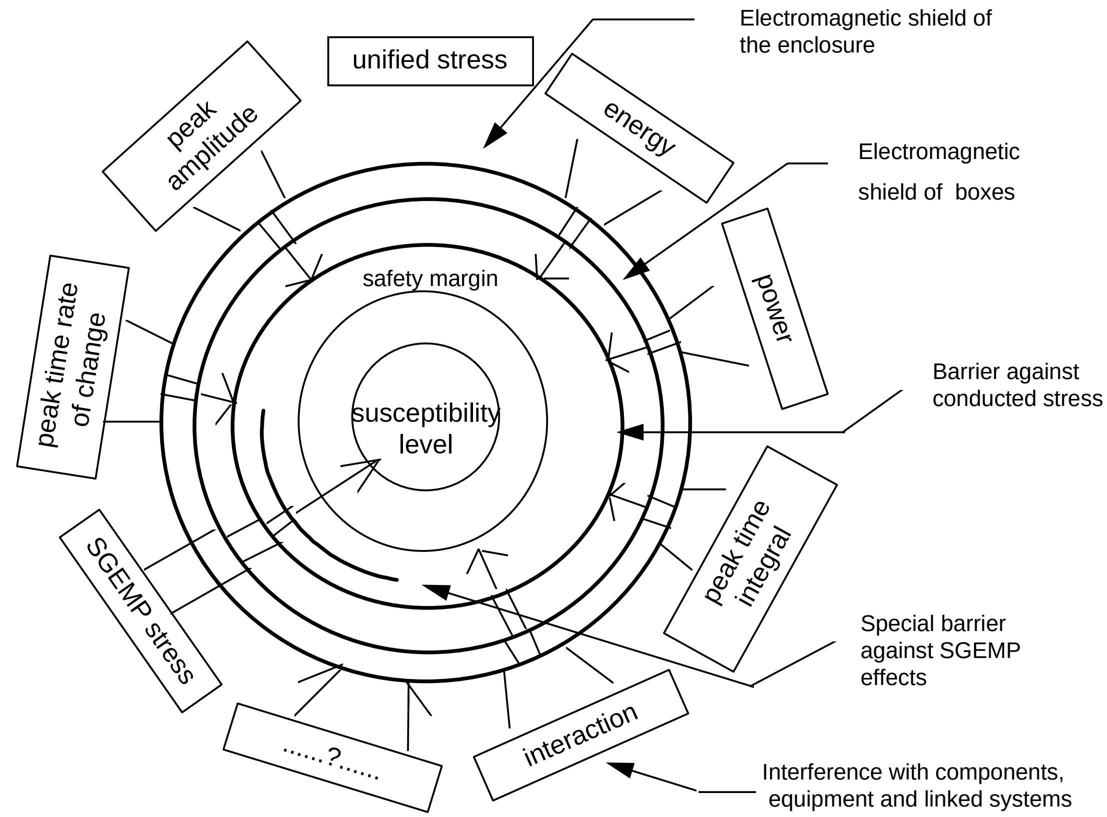


Figure 6. Centric Illustration of the Barrier Concept Reducing the Number of Barriers by Exploiting all Protection Properties of a Special Barrier

4.5 PROTECTION AND HARDENING MEASURES

The right choice and installation of protection and hardening measures are mainly responsible for the overall cost of the EM protection during the life cycle of material. With respect to this, there exist a lot of experiences in the area of NEMP-protection or EMC in general. The consequence is, that for each EME an optimal protection solution should be available. But, these classical protection solutions are typically not optimised in the sense of UE^3. The focus of this chapter is to give a guideline for engineers who are familiar with classical EMC-protection to design an optimal UE^{3}P.

Table 3. Typical UE^{3}P Options

		Protection and Hardening Measures							
External Environment	**Type**	SH	NL	SC	FI	IN	GR	EMC	SG-EMP
Near Strike Lightning (NSL)	R	X					X	X	
	C	X	X		X	X	X	X	
Direct Strike Lightning (DSL)	C	X	X		X	X	X	X	
High Altitude Electromagnetic Pulse (HEMP) E1, E2, E3	R	X					X	X	
	C	X	X	X	X	X	X	X	
Source Region EMP (SREMP)	R	X					X	X	X
	C	X	X	X	X	X	X	X	X
Non-Nuclear EMP (N^2 EMP)	R	X		X	X	X	X	X	
Electromagnetic Emissions	R	X					X	X	
	C	X			X		X	X	
High Intensity Radiated Field (HIRF)	R	X	X		X		X	X	
Electronic Counter Measures (ECM)	R	X			X			X	
High Power Microwave (HPM)	R	X	X	X	X	X	X	X	
Ultra-Wideband (UWB)	R	X					X	X	
	C	X	X		X	X	X	X	
Electrostatic Discharge (ESD)	R	X					X	X	
	C	X	X	X	X	X	X	X	
System Generated EMP (SGEMP) External	R	X					X	X	X
	C	X	X	X	X	X	X	X	X
Dispersed EMP (DEMP)	R	X					X	X	X
	C	X	X	X			X	X	X
Intern. Environment									
Electromagnetic Emissions	R	X					X	X	
	C	X			X		X	X	
Electrostatic Discharge (ESD)	R	X					X	X	
	C	X	X	X	X	X	X	X	
SGEMP – Internal (Box and Cable)	R	X					X	X	
	C	X	X	X	X	X	X	X	X

R – Radiated C – Conducted

SH EM shielding NL non-linear device SC short-circuit current limitation
FI filter IN insulation GR grounding EMC EMC design measures
SGEMP special SGEMP protection measures

Notes: This table provides typical guidelines. There are exceptions. Where shielding is identified against conducted stress (C), then it is used to control spatial emission, or cross-talk, or translation of radiated fields into conducted interference.

4.5.1 Electromagnetic Barriers

4.5.1.1 EM Shielding Electromagnetic shielding is one of the most important unified protection measures. Because, if established correctly, EM shielding can protect electronics against the whole EME and can be used for dual use protection as described below. This protection measure is very well suitable for UE^{3}P for various reasons: This is essential for the topological concept; The shielding effectiveness of different material and design types (solid, lattice, gaskets, absorber material, ITO coating, conductive finishes, wave guide) is well defined (see Vol. III); The value of the shielding effectiveness is frequency dependent and therefore this is typically presented in the frequency domain, so it is easy to use for different EMEs; The value is linear to the EM field amplitudes, but there are exceptions. The exceptions are for example, the rusty bolt effect, shielding with permeable material and the melting of the shielding material by very strong fields or currents (DSL).

The finding of the optimum shielding material and design type needs an understanding of complex linkages. The linkages are between all system requirements (mechanics, optics and electromagnetics). The following considerations are given as a first view of the problem.

The material of the shield has to withstand the expected highest energy/power stress. It is possible to avoid possible energy effects from battlespace environment to equipment inside of an enclosure. An EM shield can deal also as mechanical and radiation protection. The use of absorber material can reduce the radar cross section of a system, the Q inside the enclosure and reduce the effect of spallation cause by the impact of a projectile against the wall.

Every shield has apertures. Otherwise, the shielded space has no possibility to communicate with the external environment. These apertures are imperfect shielding material (e.g. non ideal conductivity or permeability) and penetrations (air conditioning vents, entrances, communications and power supply conductors). These penetrations have to be controlled to provide the required shielding effectiveness.

4.5.1.2 Penetration Control Penetrations are essential for every usable shielded enclosure that has contact with the external environment. The penetration controls are a barrier against conducted and radiated stresses, whereas the shield of the enclosure is a barrier against radiated stresses only. Penetration controls are necessary to provide the required shielding effectiveness (see Para 4.5.1.1). Penetration controls can be separated into linear and non-linear EM barriers (see below). Depending on the EME, linear or non-linear or a combination of both EM barriers are necessary to provide the required protection. The penetration control barriers are often concentrated in a shielded box on the passage between topological zones. This box protects the internal enclosure against the EM fields that are generated by the external residuals of the used protection devices.

4.5.1.2.1 Linear Devices Linear devices act on a sinusoidal wave in a way that only the amplitude at a given frequency changes, however, the image is still a sinusoidal wave at the same frequency. This is the case for a linear system and possess the property of superposition. In reality, linear devices do have only the property of linearity within its defined specifications. Usually for frequencies or amplitudes outside the defined specifications, the “linear device” may act non-linearly. Linear devices are used as an EM barrier, e.g., shielding, a high frequency waveguide beyond cut-off (single or array type), filters (see Para 4.5.2), insulation (see Para 4.5.4) or earth ground (see Para 4.5.5).

4.5.1.2.2 Non-Linear Devices Non-linear devices are used typically to protect electronics against high voltage spikes, which are transmitted on conductors. As shielding, this protection measure is also very important for UE^{3}P, because the stress of high voltage spikes induced by the whole EME on conductors can be bound using these devices. The bases for selection of the non-linear devices (spark gaps, varistors, suppressor/transorb diodes, hybrid transient protectors) are the induced stresses on conductors in the time domain and their correlated EM effects. Knowing the induced stress it is possible to generate a unified stress (US) for the non-linear device, using waveform norms. The set of US parameters contains at least the information of the maximum induced peak amplitude (voltage, current), peak derivative and energy with respect to the considered conductor. With these data, it is possible to gather information of available non-linear devices that fit best:

1. compare the data of US with the technical data of available non-linear devices
2. determine the internal residual US considering the non-linear devices
3. correlate the internal residual US with the remaining EM effects.
4. decide whether the remaining EM effects can be accepted or rejected, the latter requires the use of additional protection measures (e.g., using additional shielding, filters or other protection devices)

4.5.2 Short-Circuit Current Limitation One important damage mechanism is a secondary breakdown in electronics. This breakdown generates permanent damage as a result of insulation destruction, e.g., by melting. Often, the stored energy in the electronic device and not the deposited energy of the EME is the source for the melting process. In this case, short-circuit limitation may be a measure to avoid secondary breakdown. For example, it could be possible to limit the short-circuit current of a battery by a resistor.

4.5.3 Filter The use of filters is common in EMI protection. An important consideration in filter selection is source and load impedance. One special aspect should be attended to. If high voltage transients are expected on inputs or outputs of filters, it is important that the transients arrive first to the capacitor and not to the inductor. Incorporation of these selection measures enhances the survival of filters against damage.

4.5.4 Insulation Insulation is necessary for different aspects in the area of EMC. Apart from common use, uncontrolled flash-over between conductors or undesired ground loops can be avoided by insulation of conductors or housings of electronics. There exist different insulation techniques (over head lines can be insulated using insulator of ceramics, buried cables with dielectric coating, or surface lines and coaxial cables can be insulated using dielectric coating). The insulation of supply lines using dielectric coating has an advantage over ceramic stand-off insulators with respect to protection against high voltage spikes that can exceed the insulation capabilities. That is, if a high voltage spike penetrates the insulator coating, the coating can extinguish the flash over of a transient, preventing a short circuit arc from being initiated. For the alternative, using insulators instead of dielectric coatings, a short circuit arc can be ignited that would burn until the supply voltage for the arc is below the necessary sustainment amplitude. If the supply voltage is provided by a high capacity battery with low internal impedance, the line can melt (see Para 4.5.2). For overhead power lines, self-extinguishing spark gaps are employed to prevent damage to the power lines.

4.5.5 Earth Ground To establish the right grounding concept is very important to achieve EMC. Moreover, it can reduce the EM coupling of incident EM fields into cabling. Special information is presented in an EMP Engineering Practices Handbook [NATO FILE 1460]. The use of non-metallic material like conductive/non-conductive Carbon Fiber Composites (CFC) leads to new grounding concepts (Examples include floating grounds for vehicles or the near-surface conductive mesh for lightning protection of aircraft, which can be largely made of CFC).

4.5.6 EMC Measures Volume V will not introduce the protection and hardening measures related to EMC. This would be outside the scope of this document. Also, in these discussions, EMC encompasses EMI. Obviously, a developer of an electronic system has to have expertise in the area of EMC. In principle, the concept of UE^{3}P and the concept of EMC complement each other. For example, if an electronic system were developed in accordance with EMC regulations, it is expected that this system will be less vulnerable than an electronic system that was developed in disregard to the EMC regulations. In the latter case, to achieve UE^{3}P after the development is expected to require more effort and cost. Inadequate EMC design considerations can result in poor bonds and grounds, increasing cable coupling or cross-talk, and lead to lower thresholds of interference. Therefore, additional protection to include some re-design may be required.

4.5.7 SGEMP Measures The SGEMP Measures are presented in AEP-20 (Mobile Shelter in the Source Region).

4.6 Selection of Unified Protection and Hardening Tools

This paragraph will illustrate how the protection and hardening tools can be implemented into an UE^{3}P concept.

4.6.1 Association of Barriers with Unified Stress Parameters

UE^{3}P is based upon the barrier concept (see Fig. 1 and 2). The intent of using barriers is to provide a bounded EME to MSCEs. The EME is bounded with respect to quantities such as EM field strength, voltage and current amplitudes, and power and energy. These quantities can be described with waveform norms and related to these with unified stress parameters (see Para 4.2.2 or Fig. 5 and 6.). The unified stress parameters are quantities that provide information about the maximum stress content of the relevant external and internal EMEs. The barriers are characterised by their effect on unified stress parameters. Their purpose is to reduce these stress parameters. The relationship between the set of unified stress parameters before and after the EM barriers is described by STFs. Generally, these functions have to be determined in the time domain, which includes non-linear effects.

4.6.2 Synergetic Effects of Barriers The UE^{3}P of a system can lead to a multiple barrier topological design (see Fig. 1). In this case, synergetic effects (dependencies) exist between the barriers (see Fig. 6).

Examples for synergetic effects are:

- The shielding effectiveness for a system can be established with one overall shield or with several separate shields (overall shield plus shielded equipments or just shielded equipments). The right choice depends on the specified battlespace EMEs (see Table 1) or on possible EM interferences between MSCEs or to achieve better system upgrading performances. In case of SGEMP, the shielding effectiveness of a large enclosure like a mobile shelter, should be established with an overall shield and individually shielded equipments and cable shields (see Para 4.5.7).
- Non-linear devices can raise the level of internal residuals (e.g. generate short spikes with high frequency content). Therefore, these devices are typically shielded.
- An earth ground cable that is poorly located or grounded can lead to high levels of interference. A well located and properly grounded cable will avoid cross coupling, coupling to MSCEs, and coupling through apertures.

Examples for additional functions of barriers:

- the EM shield can fulfil additional functions in the system design. It can protect against other non-EM battlespace environments (for example, some protection against blast or climatic effects or protection against inadvertent physical impacts by operators).
- The installation of filters and non-linear devices can increase the reliability of the system even in a non-battlespace environment (reducing the normal system noise level enabling greater usage of more sensitive devices such as COTS).
- Improves security of sensitive operations and reduces TEMPEST concerns

4.6.3 Determination of the Necessary Barrier Performance. The determination of the necessary barrier performance will usually result in a complex process (see Vol I, Para 4.1.5.2.2). At the beginning of this process, the mission requirements, the specified EMEs, specified hardware performance, and economic considerations are involved. Then a system hazard analysis is required (determine hardware criticality and upset criteria). For a specified EME, the necessary barrier performance depends mainly on the susceptibility of the MSCEs and the specified safety margin of the system. The procedures to determine the susceptibility levels and safety margins are discussed in Volume IV. The result of the allocation equations yields the necessary barrier performance parameters (see Fig. 2). Additionally, synergetic effects of the barriers have to be considered in optimizing the UE^{3}P design (see Para 4.6.2 and 4.6.4 below).

4.6.4 Guidelines for the Optimisation of a Barrier Concept. The impetus for the optimisation of the barrier concept is related to economic considerations and required system performance. The principle of the optimisation of the barrier concept is shown in Fig. 5 and 6. Basically, there are two cases, incorporating equipments and/or subsystems into an existing system/platform or designing a new system/platform. See paragraphs 4.6.7 and 4.7.1 below.

4.6.5 Interaction of Barriers with System Specifications Barriers can positively and negatively interact with the system specifications. Examples for positive effects are listed in Para 4.6.2. Examples for negative effects are:

The installations of barriers

- may lead to undesired additional weight of a system
- need space and that can reduce the compactness of a system
- may have an effect on the installation place of the equipment, because the EM coupling on the equipment depend on their distance to conductors and to apertures of a system enclosure
- can increase the effort for the maintenance and for the upgrading of a system
- may reduce the possible bandwidth of communication lines and of antennas (e.g. filters or varistors)
- may change the effect of camouflage (e.g. metal shield can increase the radar cross section of a system)
- can raise the total costs of a system and because of budget restrictions EM hardening compete against other system specifications

The negative effects may lead to priority questions and its clarifications.

4.6.6 Ageing Effects of the Barriers and of the Susceptibility Level on the Electronic Components

Obviously, the sustainment of barrier properties and of susceptibility levels on electronic components are essential to preserve the safety margins of a system. Unfortunately, their sustainment is usually affected by ageing. The kind and the grade of ageing effects have to be known. This knowledge is needed to lay down the schedule for maintenance intervals, which of course can also be manipulated by changing the level of safety margins (see also Para 4.7.5). The ageing effects depend on different causes. See Para 4.7.4 with respect to ageing effects to protection measures. The ageing effects on electronic components can result at least to a decrease of their susceptibility levels or even more to a failure of an electronic component during normal operation. These risks can be kept low by regular inspections and maintenances and responsive repairs/replacements (see Para 4.3.2.4.2 d. , Volume II).

4.6.7 The Implications of Modernisation and Upgrades on Hardening and Protection Measures

The hardware must remain E^3 survivable for much longer periods of deployment (>50 years for many) while accommodating multiple upgrades and modernizations (see Para 4.1.1 Volume I). Therefore, it may be necessary that modernisations and upgrades (MaU) of future equipment need also MaU on hardening and protection measures. More over, the EME requirements of a system can become more severe during such a long expected period of deployment. That can lead to the same situation as to replace equipment that has a higher susceptibility level with equipment that has a lower susceptibility level. The risks for necessary MaU on hardening and protection measures can be kept low by adding additional safety margins to the system from the outset. Then, the hardening and protection measures have to be only upgraded if these additional margins were not sufficient any more. The costs for MaU on existing (build in) hardening and protection measures (e.g. shielding and penetration protection) are of course lower then for non existing hardening and protection measures (e.g. may lead to space problems in compact systems, the MaU of hardening and protection measures are not possible with the method of replacements). If the MuA lead to a replacement of larger boxes with smaller boxes it may be possible to add additional protection to these smaller boxes. In this case, the implications of MaU on hardening and protection measures can be lower (see Para 4.7.2.3).

4.7 Insertion of UE^{3}P into the Life-Cycle Concept of Defence Material

The application of UE^{3}P should start early into the hardware's life-cycle, as in established classical EMC protection measures. Then the necessary protection measures can be integrated into the systems design and can even fulfil supplementary functions, e.g., the housing of a system can serve as EM shield, special cabling and/or routing can avoid crosstalk, the modular separation of electronics and accommodation in equipments can improve the internal EME for the protected MSCEs, which allows the wider use of COTS, and future upgrades and modernisations.

4.7.1 Development of Systems and Equipment. The knowledge of the survivability requirements of the system (see Vol. II) and the immunity levels of MSCEs (see Vol. IV) are the basis for the implementation of UE^{3}P into the hardware's development. In principle, most of the procedures in the development and deployment phases are comparable to those needed to establish classical EMC protection; but, in addition to the requirements, the protection and the hardening measures and their validation have to be unified. The unification has to be done for the frequency and for the time domain response of the system. It is also necessary to consider both the linear and the non-linear EM effects to achieve balanced protection and hardening measures, and maintain margin.

4.7.2 Life-Cycle Integration of COTS Products.

4.7.2.1 General The push towards the use of commercial-off-the-shelf equipment could lead to systems that are more vulnerable if incorrectly handled. Overall, most COTS equipment has lower EME requirements than military equipment and therefore do not have the same reliability as military products when exposed to high level EM fields. During EMC testing, hardware is exposed to specified EM field and/or current levels (the pass/fail or survivability level) of EME to see if it operates correctly. For major systems, testing is normally performed at 6 dB over the specified EM levels to provide additional confidence in the results due to small test sample size. If the system meets its operational performance requirements at these levels, then it is deemed to have passed. In some military test specifications, there is an additional higher “over-test limit“ requirement for systems providing a critical function (such as ordnance, flight safety hardware is exposed to higher stress levels to determine at what level the test system ceases to operate correctly (the vulnerability level). This provides a measure of the margin in its immunity. Unfortunately, current civil EMC testing procedures do not require EMV testing to define margins. Therefore, although the hardware may be electromagnetically harder than the EMC test levels it was tested to, for the civil requirements, the EMV thresholds and margins are not known. It is recommended that the COTS equipment be tested to a standard like AECTP 500 to determine its immunity level. It may be necessary to add additional protection “barriers” to reduce the “worst case” coupled or radiated EM fields to acceptable levels that will meet the operational performance requirements with margin. The disadvantage of this approach is the cost and time implications to the COTS manufacturer or system integrator. Additional testing may be required. However, if testing is not performed, then added protection may be required that could be excessive and costly.

The barrier protection concept is equally applicable to the use of COTS electronics. The requirements for the barrier are defined in terms of the required hardness of the equipment and its known EMC performance in the defined EME. The types of barriers to be employed depend on the type of COTS and other installation requirements and will have to be made on a case-by-case basis. In addition, the user has the choice of augmenting the COTS immunities by increasing the barrier performance requirements, or accepting higher risk of mission degradation.

While COTS can be used with the barrier protection concept, there are many other issues such as temperature, vibration, ruggedness related to COTS integration that should be addressed as part of the decision to use COTS. As some of these issues are not EM protection issues, they are not the subject of this AEP. Of concern to the EM protection issue is the problem of technology stability. Military systems may have relatively long production runs that require procuring the same COTS over long time periods. COTS technologies, especially digital, have relatively short production cycles, which are outside the control of the military that is a relatively small user. These production cycles involve items such as circuit redesign and packaging, and integrated circuit performance changes (increased inherent operating speed, optical ports, feature-size reduction and reduced power supply requirements), which may have a negative impact on their EM hardness. Sample immunity testing may be required to confirm that the allocated immunity is controlled for all production items.

However, in all cases, civil requirements do not mandate protection against NEMP, HPM, and UWB and therefore consideration will have to be given to protecting against these EMEs if part of the system requirements.

4.7.2.3 Discussion on Hardening Measures which may be Required for COTS Equipment

The EM protection afforded by the enclosure surface of many military assets such as standard buildings, air vehicles, or even some light armoured vehicles is not significant, certainly not in the microwave frequency band. In the latter case, energy penetration is primarily through leakage around hatches and seams, cables penetrations, and optics. As for other more open vehicles such as tactical vehicles, one can assume that there will be minimal EM protection. Specialised installation and shielding procedures may be needed to provide the additional EM protection required for the deployment of equipments, especially COTS equipment. In the case of metallic naval vessels, a higher degree of protection may be expected for equipment mounted “below decks” due to inherent construction attenuation. This assumption is made in Naval equipment EMC requirements.

In considering additional hardening of COTS equipment or systems, the following factors have to be considered:

- Impact on maintenance requirements. Will the additional protection measures require special in-service maintenance e.g., checking of back-shell torque on shielded cables, replacement of gaskets
- Cost. One of the main reasons for employing COTS equipment is to reduce costs of system development or modifications/upgrades. It is therefore beneficial if the cost of the protection measures do not negate the cost savings obtained by procuring COTS equipment.
- Implementation. How easily can the additional protection measures be installed, either on the COTS or in the asset in which the COTS is installed? In addition, any negative impact on the operational performance requirements of the equipment or the asset needs to be determined.
- Enhancement. The performance life span of COTS may be short compared to the life span of military hardware. New upgraded versions or next generation of COTS may be available in a period less than a year. This is particularly true for digital devices. Consequently, the average number of replacement cycles for major military hardware has increased from one (30 years) to as many as ten (40 years). Some major benefits of COTS usage in military hardware are reduced cost, the enhancement of performance as well as mission capabilities. Usually, COTS are less expensive than military quality devices and for a system, the cost savings can be significant. Another major enhancement is technology superiority of COTS devices over military devices of the same family, often by two or more generations. COTS developments are driven by rapid changing commercial markets that are very competitive and are much larger than the military market.

Availability and obsolescent[1]: With respect to replacements of COTS, it is desirable that the availability of COTS over a longer period of time will be

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[1] to enhance staff

possible. Unfortunately, the performance life span of COTS may be short compared to the life span of military hardware (see above). Therefore, the use of COTS may lead to an obsolescent problem. This problem may be solved by a storage management of COTS products.
The main COTS protection options in order of level of application are:

- **Relocate:** If a relatively small degree of additional protection is required, then relocation away from apertures such as doors and windows may reduce the EM environment at the COTS equipment to acceptable levels.
- **Add an outer shielded barrier:** This covers such procedures as fitting an outer case around the equipment or installing shielded rooms inside buildings or establishing zones inside platforms to house COTS equipment. Simpler lower cost protection methods for buildings include using conductive coatings and wall dividers utilizing EM absorbent material for less critical systems, and the use of EM shielded windows. Shielded windows can also be used to harden vehicles. In the case of fabric covered facilities such as soft topped vehicles or tents, conductive fabrics are available which provide a useful degree of EM shielding. Conductive cement building blocks are coming onto the market for new building construction and these can provide a reasonable degree of shielding. CFC structures can be made into effective conductive shields by impregnation with conductive mesh/particles and/or coated with conductive spray.
- **Additional cable protection:** In the case of power supply cables, filtering and/or transient protection devices can be installed. The Defence Threat Reduction Agency in the USA has an ongoing programme to develop replacement cables for COTS Information Technology (IT) equipment containing integral filters, screening and EM lossy protection elements.

  For control and signal lines, additional over-braid can be used or they can be run in conductive conduit or raceways. On PCs, it may be necessary to fit lossy suppression elements over interconnecting leads such as to the keyboard, mouse and display.

  The use of fibre optics instead of electrical wiring for control and signal lines and networks should also be encouraged.
- **Modify the COTS equipment case:** The intention is to minimise any apertures through which EM Fields can couple to the internal circuitry. Examples of EM protection measures include fitting conductive screens over any displays, improving bonding at case joints, and metallising any non-conductive case panels.
- **Modify the COTS equipment internally:** This is generally a last resort as it involves re-designing the equipment and has cost and schedule implications. Examples include fitting additional filtering on circuit boards or on internal power supplies.

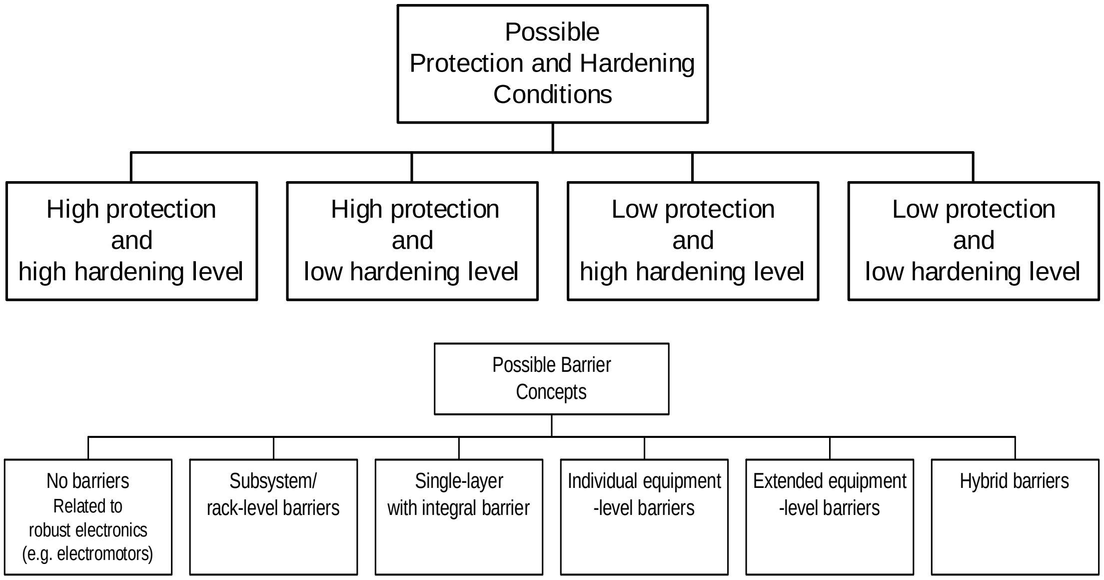
4.7.3 Upgrading of Inadequate Protection

An upgrade of the EM protection performance will be necessary if systems / facilities do not meet the EM requirements. This can impact the success of a mission. Inadequate protection can lead to unnecessary maintenance costs or the exclusion of benefits from future upgrades and modernization programs (for example, the wider use of COTS). The effort required to upgrade inadequate protection measures depends on the quality of the existing protection level achieved and on the EM topology (see Vol. I, Section 3.2) of the system. Obviously, the effort to increase protection to a low level is less than that required to increase protection to a high level. The effort to upgrade a single layered EM topology is less than that of a complex multi-layered EM topology.

Depending on the EM protection performance and the available budget, the later realisation of a 100% protection of a system/facility can be too expensive (e.g., the later installation of an overall shielded enclosure of an underground facility). However, a partial upgrade of the protection measures can be affordable to increase at least the confidence level by maximizing existing resources. This can lead to partial shielding of MSCEs, insertion of surge protectors and filters at interfaces, and storage of highly endangered MSCEs in systems/facilities for fast replacement.

A typical choice of starting points are listed the following (see Organ gram 1).

Upgrading of Inadequate
Protection of Military Hardware



Organ gram 1: Possible Protection and Hardening Conditions and Barrier Concepts

Risk Assessment

It is important to tailor the EM protection requirements for the hardware being procured to those needed to ensure that the various required system operational performances are met.

Over-specifying the EM protection requirements will lead to over-engineering and thus incur cost penalties. On the other hand, under-specifying may lead in failure to meeting operational performance requirements and even larger costs to correct and then to retro-fit the family, which could be very large number. A degree of system degradation may be permissible and it may not be necessary for all the equipment in the system under consideration to work all the time especially if there is built in system redundancy. The criticality of the system function also impacts on what protection is required. If non-critical, then minimal hardness may only be needed. An assessment is required at this step to determine the impact on the overall operational requirements of the asset, if the system under consideration failed. Does the asset itself need to operate through all EME or is it just required to survive an event such as Lightning, NEMP, HPM, UWB, but be fully functional in the "every day EM environment"?

4.7.4 Ageing Effects on Protection Measures. The understanding of ageing effects is necessary to ensure continued EMC and determine the survivability level of the system during full life-cycle. For understanding the importance to the life-cycle of systems, the following interdependent parameters like the ageing rates of protection measures, mean time between failure rates, DMSMS, the ageing effects on safety margins and the maintenance interval are relevant. These parameters can be measured by dedicated experiments. The ageing effects and rates are dependent on the selection of the protection measures (e.g., solid or lattice shield), the used materiel (e.g., stainless steel, tinned copper, monel and permalloy), the design (e.g., braid shields, solid metal cable and metallised plastic) and the construction (e.g., bolted or weld joints, glued or soldered honeycombs). Furthermore, the effect of ageing is frequency dependant and also dependant on the operating environment of the system/equipment. A variety of ageing effects on protection measures can be determined with the proposed procedures in Vol. VI, Section 11, on well defined degraded systems. Ageing effects can be accelerated from inadequate maintenance procedures and cycles, and should be discovered by surveillance tests (see Para 4.3.2.5 of Volumes II and VII). If surveillance tests are not performed, then the barrier ageing effects may be highlighted or worst-case, discovered as a mission failure.

UE^{3}P can reduce the negative impacts of aging effects. Properly located, constructed, and maintained barriers can oftentimes provide sufficient E^3 protection to MSCEs for a longer period of time than other protection methodologies. UE^{3}P can also reduce maintenance costs because fewer barriers may be required. Unification of EME testing will reduce costs and schedules, and number of tests performed. These factors reduce the overall cost of hardness and sustainment assurance.

4.7.5 Protection Measures Concerning Ageing Effects. Additionally, protection measures have to be taken into account to guarantee the recommended survivability level of the system during full service life. Whether an increase of the safety margins is sufficient to provide an adequate confidence level depends on technical and economical considerations. The use of high-quality products (e.g., the use of corrosion resistant materiel or the use of welded joints) can reduce the maintenance periods and costs, and could be therefore economically justified. This is discussed in more detail in Volume VII.

5.0 SUMMARY

The proposed UE^{3}P approach can be applied to all six OCs of NATO military hardware. For all six OCs, the method of achieving UE^3 protection and survivability is principally the same. The method depends on a barrier concept and on the unification of relevant EMEs (external and internal). The barrier is defined infinitively good. That means for example, also the propagation of an EM field through air can be a barrier, if the propagation reduces the stress content of the incident EM field. The unification of relevant EMEs is e.g. possible by comparison the stress content of the EMEs (external and internal). The comparison is based on waveform norms (see Table 2) that can be linked to the susceptibility levels and effects. The UE^{3}P depends not on realizing unified waveforms, but on excluding waveforms from relevant EMEs. The maximum stress content of the relevant EMEs can be combined to a quantity named US (see Para 4.2.2). The relation between the stress content of the radiated and conducted stress before and after penetration through a barrier can be described with a STF. The goal of UE^{3}P is to reduce costs for the whole life cycle of military hardware. The general concept is to avoid redundancies on protection measures and on tests using the knowledge of all relevant EMEs not separately but combined.

6.0 CONCLUSIONS

Volume V serves as a guideline to achieve UE^{3}P to reduce the costs of development, construction and sustainment by the exclusion of supplementary, conflicting and redundant measures.

7.0 APPENDIX

7.1 LIST OF NATIONAL POINTS OF CONTACT

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7.3 ACRONYMS

Abb	abbreviation
AC	alternating current
AEP	allied engineering publication
ANSI	American National Standards Institute
CNAD	Combined National Armaments Directors
COTS	commercial off the shelf
dB	decibel
DEMP	disperse EMP
DMS	diminishing manufacturing sources
DMSMS	diminishing manufacturing sources & material shortages
DSL	direct strike lightning
EED	electro-explosive device
EID	electrically initiated device
EM	electromagnetic
EMC	electromagnetic compatibility

EME	electromagnetic environment
EMI	electromagnetic interference
EMP	electromagnetic pulse
E^3	electromagnetic environmental effects
HA	hardness assurance
HEMP	high-altitude electromagnetic pulse
HIRF	high intensity radiated field
HPM	high-power microwave
IEC	International Electro-technical Commission
IEMP	Internal EMP
LRU	line replaceable unit
QA	quality assurance
QC	quality control
QSTAG	quadripartite standardization agreement
MHz	megahertz
MIL-STD	military standard
MOV	metal oxide varistor
MSCE	mission and safety critical electronics
MTS	modernization-through-spares
NATO	North Atlantic Treaty Organization
NDI	none developmental item
NLE	non-linear effects
NSL	near strike lightning
P	power
PCB	printed circuit board
PARA.	paragraph
POE	point of entry
P-STATIC	precipitation static
RADHAZ	radiation hazard
RE	radiated emissions
RF	radio frequency
RS	radiated susceptibility
UBPR	unified barrier performance requirement
UE^3	unified electromagnetic environmental effect
UE^3P	unified electromagnetic environmental effect protection
US	unified stress
USA	United States of America
μs	microsecond
UWB	ultra wideband
V/M	volts per meter
VOL.	volume
SA	sustainment assurance
SGEMP	system generated EMP
SREMP	source region EMP
ST	surveillance test
STF	stress transfer function