NOT MEASUREMENT
SENSITIVE

MIL-STD-464
18 March 1997

SUPERSEDING
(See section 6.5)

DEPARTMENT OF DEFENSE INTERFACE STANDARD

ELECTROMAGNETIC ENVIRONMENTAL EFFECTS

REQUIREMENTS FOR SYSTEMS

AMSC A7252

AREA EMCS

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

FOREWORD

1. This Military Standard is approved for use by all Departments and Agencies of the Department of Defense.

2. This standard is in compliance with the Acquisition Reform Initiatives of Dr. William Perry's memo dated 29 June 1995 (see 6.8).

3. This standard contains two sections, the main body and an appendix. The main body of the standard specifies a baseline set of requirements. The appendix portion provides rationale, guidance, and lessons learned for each requirement to enable the procuring activity to tailor the baseline requirements for a particular application. The appendix also permits government and industry personnel to understand the purpose of the requirements and potential verification methodology for a design. The appendix is not a mandatory part of this document.

4. A joint committee consisting of representatives of the Army, Navy, Air Force, other DoD Agencies, and industry participated in the preparation of this standard.

5. Comments and data which may be of use in improving this document should be addressed to: USAF/Aeronautical Systems Center, ASC/ENSI, 2530 Loop Road West, Wright-Patterson AFB, OH 45433-7101, by using the Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

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APPENDIX

1. SCOPE

1.1 Purpose. This standard establishes electromagnetic environmental effects (E^3) interface requirements and verification criteria for airborne, sea, space, and ground systems, including associated ordnance.

1.2 Application. This standard is applicable for complete systems, both new and modified.

2. APPLICABLE DOCUMENTS

2.1 General. The documents listed in this section are referenced in sections 3, 4, and 5 of this standard. This section does not include documents cited in other sections of this standard or recommended for additional information or as examples. While every effort has been made to ensure the completeness of this list, document users are cautioned that they must meet all specified requirements documents cited in Section 4 and 5 of this standard, whether or not they are listed.

2.2 Government documents

2.2.1 Specifications, standards, and handbooks. The following specifications, standards, and handbooks form a part of this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those listed in the issue of the Department of Defense Index of Specifications and Standards (DoDISS) and supplement thereto, cited in the solicitation (see 6.2).

STANDARDS

Department of Defense

MIL-STD-331	Fuze and Fuze Components, Environmental and Performance Tests for
MIL-STD-461	Requirements for the Control of Electromagnetic Interference Emissions and Susceptibility
MIL-STD-462	Measurement of Electromagnetic Interference Characteristics
MIL-STD-1399-070	Interface Standard for Shipboard Systems, D.C. Magnetic Field Environment

(Unless otherwise indicated, copies of federal and military specifications, standards, and handbooks are available from the Standardization Documents Order Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.)

2.2.2 Other Government documents, drawings, and publications. The following other Government documents, drawings, and publications form a part of this document to the extent specified herein. Unless otherwise specified, the issues are those cited in the solicitation.

PUBLICATIONS

DoDD 4650.1	Management and Use of the Radio Frequency Spectrum
DoDI 6055.11	Protection of DoD Personnel from Exposure to Radio Frequency Radiation and Military Exempt Lasers
NACSEM 5112	NONSTOP Evaluation Techniques
NSTISSAM TEMPEST/1-92	Compromising Emanations Laboratory Test Requirements, Electromagnetics
NTIA	Manual of Regulations and Procedures for Federal Radio Frequency Management

(Copies of NTIA Manual are available from the U.S. Government Printing Office, Superintendent of Documents, P.O. Box 371954, Pittsburgh, PA 15250-7954. Copies of DoD documents are available from the Standardization Documents Order Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094. Copies of NACSEM and NSTISSAM documents are available only through the procuring activity.)

2.3 Non-Government publications. The following documents form a part of this document to the extent specified herein. Unless otherwise specified, the issues of the documents which are DoD adopted are those listed in the issue of the DoDISS cited in the solicitation. Unless otherwise specified, the issues of documents not listed in the DoDISS are the issues of the documents cited in the solicitation (see 6.2).

AMERICAN NATIONAL STANDARDS INSTITUTE

ANSI C63.14	Standard Dictionary for Technologies of Electromagnetic Compatibility (EMC), Electromagnetic Pulse (EMP), and Electrostatic Discharge (ESD)

(Application for copies should be addressed to the IEEE Service Center, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331.)

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION

ISO 46	Aircraft - Fuel Nozzle Grounding Plugs and Sockets

(Application for copies should be addressed to ISO, International Organization for Standardization, 3 rue de Varembe, 1211 Geneve 20, Geneve, Switzerland; Phone: 41 22 734 0150).

2.4 Order of precedence. In the event of a conflict between the text of this document and the references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

3. DEFINITIONS

3.1 Acronyms used in this standard. The acronyms used in this standard are defined as follows.

E^3	electromagnetic environmental effects
EID	electrically initiated device
EMC	electromagnetic compatibility
EMCON	emission control
EME	electromagnetic environment
EMI	electromagnetic interference
EMP	electromagnetic pulse
EMRADHAZ	electromagnetic radiation hazards
EP	electronic protection
HERF	hazards of electromagnetic radiation to fuel
HERO	hazards of electromagnetic radiation to ordnance
HERP	hazards of electromagnetic radiation to personnel
IMI	intermodulation interference
ISO	International Standards Organization
MNFS	maximum no-fire stimulus
NDI	non-developmental item
p-static	precipitation static
RF	radio frequency
rms	root-mean-square

3.2 General. The terms used in this standard are defined in ANSI Standard C63.14. In addition, the following definitions are applicable for the purpose of this standard.

a. Above deck. An area on ships which is not considered to be below deck as defined herein.

b. Below deck. An area on ships which is surrounded by a metallic structure or an area which provides an equivalent attenuation to electromagnetic radiation, such as the metal hull or superstructure of a surface ship, the hull of a submarine and the screened rooms in non-metallic ships.

c. Compromising emanations. Unintentional intelligence-bearing signals which, if intercepted and analyzed, disclose the national security information transmitted, received, handled, or otherwise processed by any classified information processing system.

d. Electrically initiated device. Any component activated through electrical means and having an explosive, pyrotechnic, or a mechanical output resulting from an explosive or pyrotechnic action, and electrothermal devices having a dynamic mechanical, thermal, or electromagnetic output. Examples include bridgewire electroexplosive devices, conductive composition electric primers, semiconductor bridge electroexplosive devices, laser initiators, exploding foil initiators, slapper detonators, burn wires, and fusible links.

e. Electromagnetic environmental effects. The impact of the electromagnetic environment upon the operational capability of military forces, equipment, systems, and platforms. It encompasses all electromagnetic disciplines, including electromagnetic compatibility; electromagnetic interference; electromagnetic vulnerability; electromagnetic pulse; electronic protection; hazards of electromagnetic radiation to personnel, ordnance, and volatile materials; and natural phenomena effects of lightning and p-static.

f. Launch vehicle. A composite of the initial stages, injection stages, space vehicle adapter, and fairing having the capability of launching and injecting a space vehicle or vehicles into orbit.

g. Lightning direct effects. Any physical damage to the system structure and electrical or electronic equipment due to the direct attachment of the lightning channel and current flow. These effects include puncture, tearing, bending, burning, vaporization, or blasting of hardware.

h. Lightning indirect effects. Electrical transients induced by lightning due to coupling of electromagnetic fields.

i. Margins. The difference between the subsystem and equipment electromagnetic strength level, and the subsystem and equipment stress level caused by electromagnetic coupling at the system level. Margins are normally expressed as a ratio in decibels (dB).

j. Maximum no-fire stimulus. The greatest firing stimulus which does not cause initiation within five minutes of more than 0.1% of all electric initiators of a given design at a confidence level of 95%. When determining maximum no-fire stimulus for electric initiators with a delay element or with a response time of more than five minutes, the firing stimulus shall be applied for the time normally required for actuation.

k. Mission critical. Unless otherwise defined in the procurement specification, a term applied to a condition, event, operation, process, or item which if performed improperly, may: 1) prohibit execution of a mission; 2) significantly reduce the operational capability; or 3) significantly increase system vulnerability.

l. Multipaction. Multipaction is an RF effect that occurs only in a high vacuum where RF field accelerates free electrons resulting in collisions with surfaces creating secondary electrons that are accelerated resulting in more electrons and ultimately a major discharge and possible equipment damage.

m. Non-developmental item. Non-developmental item is a broad, generic term that covers material, both hardware and software, available from a wide variety of sources with little or no development effort required by the Government.

n. Ordnance. An explosive or pyrotechnic component or subsystem of an airborne, sea, space, or ground system.

o. Safety critical. Unless otherwise defined in the procurement specification, a term applied to a condition, event, operation, process, or item whose proper recognition, control, performance or tolerance is essential to safe system operation or use; for example, safety critical function, safety critical path, or safety critical component.

p. Space vehicle. A complete, integrated set of subsystems and components capable of supporting an operational role in space. A space vehicle may be an orbiting vehicle, a major portion of an orbiting vehicle, or a payload of an orbiting vehicle which performs it mission while attached to a recoverable launch vehicle. The airborne support equipment which is peculiar to programs utilizing a recoverable launch vehicle is considered a part of the space vehicle being carried by the launch vehicle.

q. System operational performance. A set of minimal acceptable parameters tailored to the platform and reflecting top level capabilities such as range, probability of kill, probability of survival, operational availability, and so forth.

r. TEMPEST. An unclassified, short name referring to the investigation and study of compromising emanations.

4. GENERAL REQUIREMENTS

4.1 General. The system shall be electromagnetically compatible among all subsystems and equipment within the system and with environments caused by electromagnetic effects external to the system. Verification shall be accomplished as specified herein on production representative systems. Safety critical functions shall be verified to be electromagnetically compatible within the system and with external environments prior to use in those environments. Verification shall address all life cycle aspects of the system, including (as applicable) normal in-service operation, checkout, storage, transportation, handling, packaging, loading, unloading, launch, and the normal operating procedures associated with each aspect.

5. DETAILED REQUIREMENTS

5.1 Margins. Margins shall be provided based on system operational performance requirements, tolerances in system hardware, and uncertainties involved in verification of system-level design requirements. Safety critical and mission critical system functions shall have a margin of at least 6 dB. Ordnance shall have a margin of at least 16.5 dB of maximum no-fire stimulus (MNFS) for safety assurances and 6 dB of MNFS for other applications. Compliance shall be verified by test, analysis, or a combination thereof. Instrumentation installed in system components during testing for margins shall capture the maximum system response and shall not adversely affect the normal response characteristics of the component. When environment simulations below specified levels are used, instrumentation responses may be extrapolated to the full environment for components with linear responses (such as hot bridgewire EIDs). When the response is below instrumentation sensitivity, the instrumentation sensitivity shall be used as the basis for extrapolation. For components with non-linear responses (such as semiconductor bridge EIDs), no extrapolation is permitted.

5.2 Intra-system electromagnetic compatibility (EMC). The system shall be electromagnetically compatible within itself such that system operational performance requirements are met. Compliance shall be verified by system-level test, analysis, or a combination thereof.

5.2.1 Hull generated intermodulation interference (IMI). For surface ship applications, the above requirement is considered to be met when the 19th product order and higher of IMI generated by High Frequency (HF) transmitters installed onboard ship are not detectable by antenna-connected receivers onboard ship. Compliance shall be verified by test, analysis, or a combination thereof, through measurement of received levels at system antennas and evaluation of the potential of these levels to degrade receivers.

5.2.2 Shipboard internal electromagnetic environment (EME). For ship applications, electric fields (peak V/m-rms) below deck from intentional onboard transmitters shall not exceed the following levels:

a. Surface ships.

(1). Metallic: 10 V/m from 10 kHz to 18 GHz.

(2). Non-metallic: 10 V/m from 10 kHz to 2 MHz, 50 V/m from 2 MHz to 1 GHz, and 10 V/m from 1 GHz to 18 GHz.

b. Submarines. 5 V/m from 10 kHz to 1 GHz.

Compliance shall be verified by test of electric fields generated below deck with all antennas (above and below decks) radiating.

5.2.3 Powerline transients. For Navy aircraft and Army aircraft applications, electrical transients of less than 50 microseconds in duration shall not exceed +50 percent or -150 percent of the nominal DC voltage or ±50 percent of the nominal AC line-to-neutral rms voltage. Compliance shall be verified by test.

5.2.4 Multipaction. For space applications, equipment and subsystems shall be free of multipaction effects. Compliance shall be verified by test and analysis.

5.3 Inter-system EMC. The system shall be electromagnetically compatible with its defined external EME such that its system operational performance requirements are met. For systems capable of shipboard operation, Table IA shall be used. For space and launch vehicle systems applications, Table IB shall be used. For ground systems, Table IC shall be used. For all other applications and if the procuring activity has not defined the EME, Table ID shall be used. Inter-system EMC covers compatibility with, but is not limited to, EME's from like platforms (such as aircraft in formation flying, ship with escort ships, and shelter-to-shelter in ground systems), friendly emitters and hostile emitters. Compliance shall be verified by system, subsystem, and equipment level tests; analysis; or a combination thereof.

TABLE IA. External EME for systems capable of shipboard operations (including topside equipment and aircraft operating from ships) and ordnance

Frequency (Hz)	Environment (V/m - rms)	
	Peak	Average
10k-150M	200	200
150M-225M	3,120	270
225M-400M	2,830	240

400M-700M	4,000	750
700M-790M	3,500	240
790M-1000M	3,500	610
1G-2G	5,670	1,000
2G-2.7G	21,270	850
2.7G-3.6G	27,460	1,230
3.6G-4G	21,270	850
4G-5.4G	15,000	610
5.4G-5.9G	15,000	1,230
5.9G-6G	15,000	610
6G-7.9G	12,650	670
7.9G-8G	12,650	810
8G-14G	21,270	1,270
14G-18G	21,270	614
18G-40G	5,000	750

TABLE IB. External EME for space and launch vehicle systems

Frequency (Hz)	Environment (V/m - rms)	
	Peak	Average
10k-100M	20	20
100M-1G	100	100
1G-10G	200	200
10G-40G	20	20

TABLE IC. External EME for ground systems

Frequency (Hz)	Environment (V/m - rms)	
	Peak	Average
10k-2M	25	25
2M-250M	50	50
250M-1G	1500	50
1G-10G	2500	50
10G-40G	1500	50

TABLE ID. Baseline external EME for all other applications

Frequency (Hz)	Environment (V/m - rms)	
	Peak	Average
10k-100k	50	50
100k-500k	60	60
500k-2M	70	70
2M-30M	200	200
30M-100M	30	30

100M-200M	150	33
200M-400M	70	70
400M-700M	4020	935
700M-1000M	1700	170
1G-2G	5000	990
2G-4G	6680	840
4G-6G	6850	310
6G-8G	3600	670
8G-12G	3500	1270
12G-18G	3500	360
18G-40G	2100	750

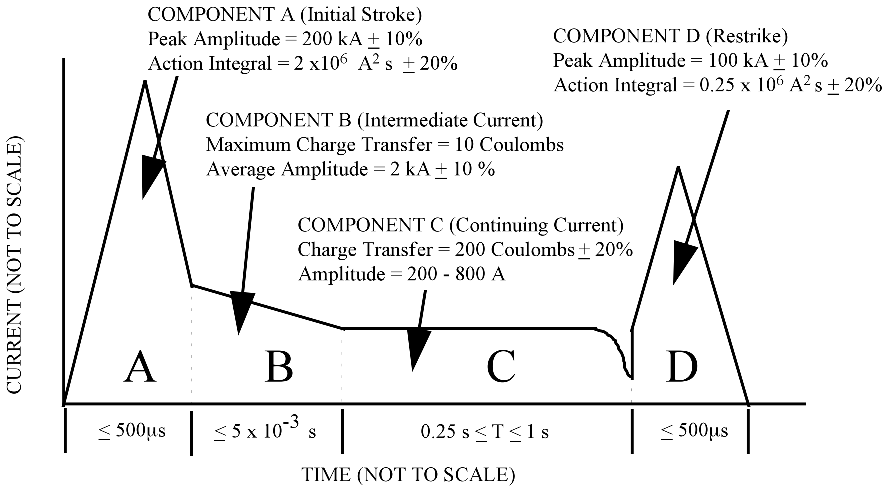
5.4 Lightning. The system shall meet its operational performance requirements for both direct and indirect effects of lightning. Ordnance shall meet its operational performance requirements after experiencing a near strike in an exposed condition and a direct strike in a stored condition. Ordnance shall remain safe during and after experiencing a direct strike in an exposed condition. Figure 1 shall be used for the direct effects lightning environment. Figure 2 and Table IIA shall be used for the indirect effects lightning environment from a direct strike. Table IIB shall be used for the near lightning strike environment. Compliance shall be verified by system, subsystem, equipment, and component (such as structural coupons and radomes) level tests, analysis, or a combination thereof.

TABLE IIA. Lightning indirect effects waveform parameters

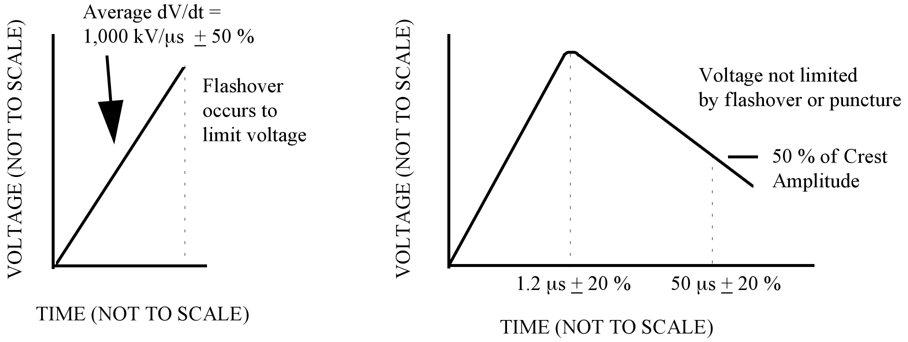
Current Component	Description	$i(t) = I_o (\varepsilon^{-\alpha t} - \varepsilon^{-\beta t})$ t is time in seconds (s)		
		I_o (Amperes)	α (s^{-1})	β (s^{-1})
A	Severe stroke	218,810	11,354	647,265
B	Intermediate current	11,300	700	2,000
C	Continuing current	400 for 0.5 s	Not applicable	Not applicable
D	Restrike	109,405	22,708	1,294,530
D/2	Multiple stroke	54,703	22,708	1,294,530
H	Multiple burst	10,572	187,191	19,105,100

TABLE IIB. Electromagnetic fields from near strike lightning (cloud-to-ground)

Magnetic field rate of change @ 10 meters	$2.2\text{x}10^{9}$ A/m/s
Electric field rate of change @ 10 meters	$6.8\text{x}10^{11}$ V/m/s



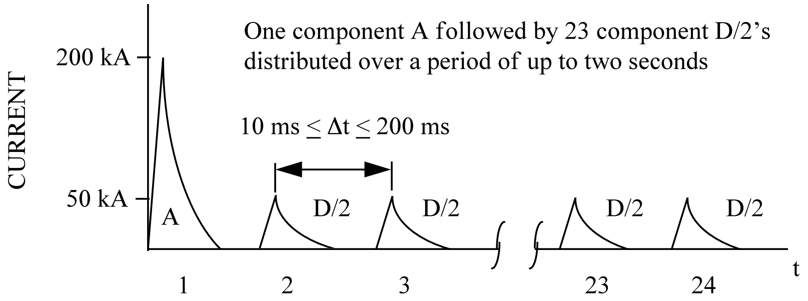
ELECTRICAL CURRENT WAVEFORMS



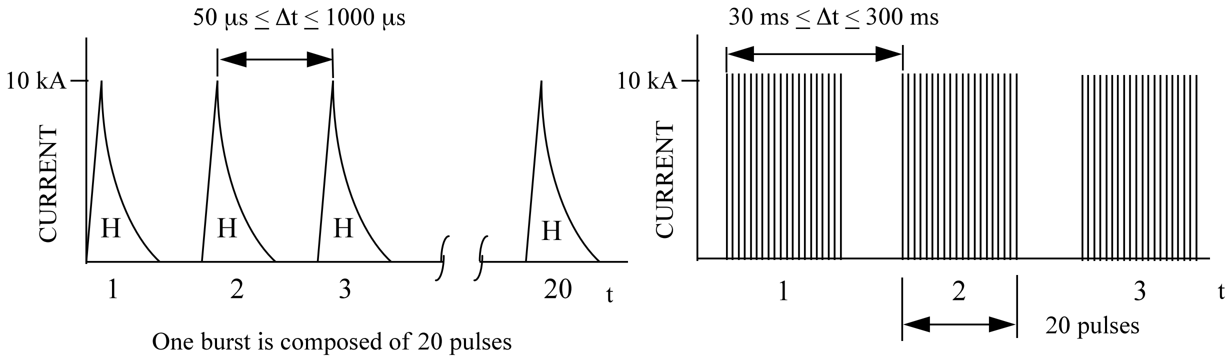
ELECTRICAL VOLTAGE WAVEFORMS

FIGURE 1. Lightning direct effects environment

5.5 Electromagnetic pulse (EMP). The system shall meet its operational performance requirements after being subjected to the EMP environment. If an EMP environment is not defined by the procuring activity, Figure 3 shall be used. This requirement is not applicable unless otherwise specified by the procuring activity. Compliance shall be verified by system, subsystem, and equipment level tests, analysis, or a combination thereof.



MULTIPLE STROKE WAVEFORM



MULTIPLE BURST WAVEFORM

FIGURE 2. Lightning indirect effects environment

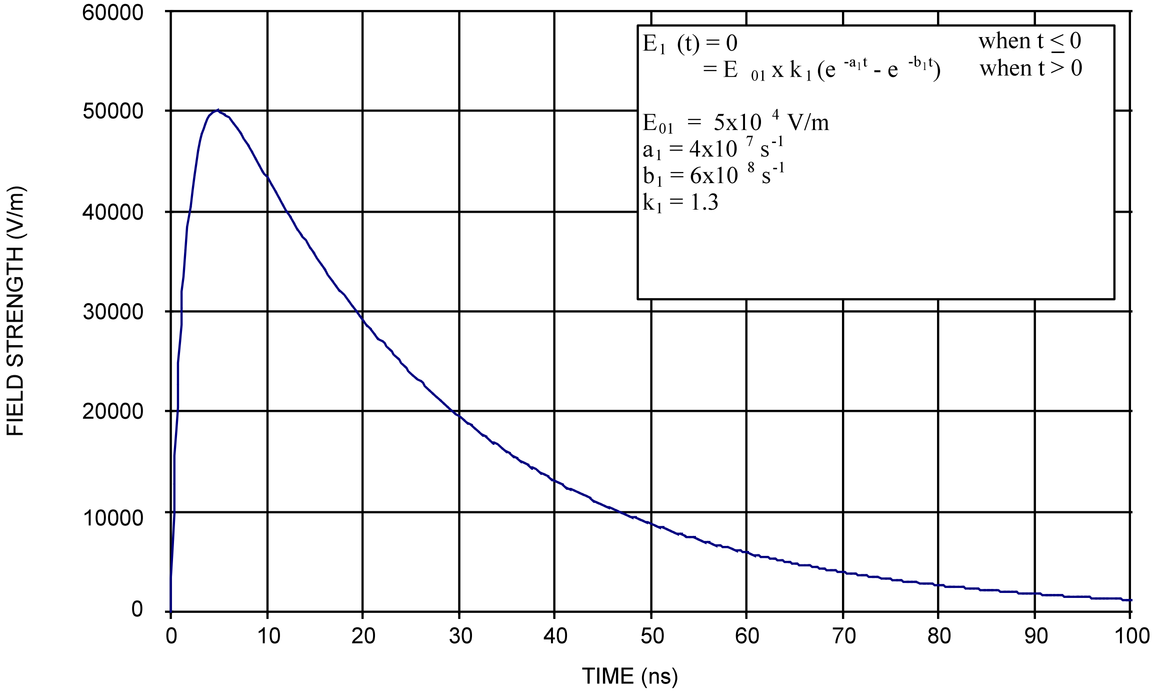


FIGURE 3. Default free-field EMP environment

5.6 Subsystems and equipment electromagnetic interference (EMI). Individual subsystems and equipment shall meet interference control requirements (such as the conducted emissions, radiated emissions, conducted susceptibility, and radiated susceptibility requirements of MIL-STD-461) so that the overall system complies with all applicable requirements of this standard. Compliance shall be verified by tests that are consistent with the individual requirement (such as testing to MIL-STD-462 to verify MIL-STD-461 requirements).

5.6.1 Non-developmental items (NDI) and commercial items. NDI and commercial items shall meet EMI interface control requirements suitable for ensuring that system operational performance requirements are met. Compliance shall be verified by test, analysis, or a combination thereof.

5.6.2 EM spectrum compatibility. Subsystems and equipment shall comply with the DoD, national, and international regulations for the use of the electromagnetic spectrum (such as NTIA "Manual of Regulations and Procedures for Radio Frequency Management" and DoDD 4650.1). Compliance shall be verified by test, analysis, or a combination thereof, as appropriate for the equipment development stage.

5.6.3. Shipboard DC magnetic field environment. Subsystems and equipment used aboard ships shall not be degraded when exposed to its operational DC magnetic environment (such as MIL-STD-1399, Section 070). Compliance shall be verified by test.

5.7 Electrostatic charge control. The system shall control and dissipate the build-up of electrostatic charges caused by precipitation static (p-static) effects, fluid flow, air flow, space and launch vehicle charging, and other charge generating mechanisms to avoid fuel ignition and ordnance hazards, to protect personnel from shock hazards, and to prevent performance degradation or damage to electronics. Compliance shall be verified by test, analysis, inspections, or a combination thereof.

5.7.1 Vertical lift and in-flight refueling. The system shall meet its operational performance requirements when subjected to a 300 kilovolt discharge. This requirement is applicable to vertical lift aircraft, in-flight refueling of any aircraft, and systems operated or transported externally by vertical lift aircraft. Compliance shall be verified by test (such as MIL-STD-331 for ordnance), analysis, inspections, or a combination thereof. The test configuration shall include electrostatic discharge in the vertical lift mode and in-flight refueling mode from a simulated aircraft capacitance of 1000 picofarads, through a maximum of one ohm resistance.

5.7.2 Precipitation static (p-static). The system shall control p-static interference to antenna-connected receivers onboard the system or on the host platform such that system operational performance requirements are met. Compliance shall be verified by test, analysis, inspections, or a combination thereof. For Navy aircraft and Army aircraft applications, p-static protection shall be verified by testing that applies charging levels representative of conditions in the operational environment.

5.7.3 Ordnance subsystems. Ordnance subsystems shall not be inadvertently initiated or dudded by a 25 kilovolt electrostatic discharge caused by personnel handling. Compliance shall be verified by test (such as MIL-STD-331), discharging a 500 picofarad capacitor through a 500 ohm resistor to the ordnance subsystem (such as electrical interfaces, enclosures, and handling points.

5.8 Electromagnetic radiation hazards (EMRADHAZ). The system design shall protect personnel, fuels, and ordnance from hazardous effects of electromagnetic radiation. Compliance shall be verified by test, analysis, inspections, or a combination thereof.

5.8.1 Hazards of Electromagnetic Radiation to Personnel (HERP). The system shall comply with current national criteria for the protection of personnel against the effect of electromagnetic radiation. DoD policy is currently found in DoDI 6055.11. Compliance shall be verified by test, analysis, or combination thereof.

5.8.2 Hazards of electromagnetic radiation to fuel (HERF). Fuels shall not be inadvertently ignited by radiated EMEs. The EME includes onboard emitters and the external EME (see 5.3). Compliance shall be verified by test, analysis, inspection, or a combination thereof.

5.8.3 Hazards of electromagnetic radiation to ordnance (HERO). Ordnance with electrically initiated devices (EIDs) shall not be inadvertently ignited during, or experience degraded performance characteristics after, exposure to the external radiated EME of Table IA for either direct RF induced actuation or coupling to the associated firing circuits. Compliance shall be verified by system, subsystem, and equipment level tests and analysis. For EME's in the HF band derived from near field conditions, verification by test shall use transmitting antennas representative of the types present in the installation.

5.9 Life cycle, E^3 hardness. The system operational performance and E^3 requirements of this standard shall be met throughout the rated life cycle of the system and shall include, but not be limited to, the following: maintenance, repair, surveillance, and corrosion control. Compliance shall be verified by test, analysis, inspections, or a combination thereof, of system design features. Maintainability, accessibility, and testability, and the ability to detect degradations shall be demonstrated.

5.10 Electrical bonding. The system, subsystems, and equipment shall include the necessary electrical bonding to meet the E^3 requirements of this standard. Compliance shall be verified by test, analysis, inspections, or a combination thereof, for the particular bonding provision.

5.10.1 Power current return path. For systems using structure for power return currents, bonding provisions shall be provided for current return paths for the electrical power sources such that the total voltage drops between the point of regulation for the power system and the electrical loads are within the tolerances of the applicable power quality standard. Compliance shall be verified by analysis of electrical current paths, electrical current levels, and bonding impedance control levels.

5.10.2 Antenna installations. Antennas shall be bonded to obtain required antenna patterns and meet the performance requirements for the antenna. Compliance shall be verified by test, analysis, inspections, or a combination thereof.

5.10.3 Electromagnetic interference (EMI). The system electrical bonding shall provide electrical continuity across external mechanical interfaces on electrical and electronic equipment, both within the equipment and between the equipment and system structure, for control of E^3 such that the system operational performance requirements are met. For Navy aircraft and Army aircraft applications, the EMI bonds shall have an interface direct current (DC) resistance of 2.5 milliohms or less for each faying interface between the subsystem or equipment enclosure and the system ground reference. Compliance shall be verified by test, analysis, inspections, or a combination thereof.

5.10.4 Shock and fault protection. Bonding of all exposed electrically conductive items subject to fault condition potentials shall be provided to control shock hazard voltages and allow proper operation of circuit protection devices. Compliance shall be verified by test, analysis, or a combination thereof.

5.11 External grounds. The system and associated subsystems shall provide external grounding provisions to control electrical current flow and static charging for protection of personnel from shock, prevention of inadvertent ignition of ordnance, fuel and flammable vapors, and protection of hardware from damage. Compliance shall be verified by test, analysis, inspections, or a combination thereof.

5.11.1 Aircraft grounding jacks. Grounding jacks shall be attached to the system to permit connection of grounding cables for fueling, stores management, servicing, maintenance operations and while parked. ISO 46 contains requirements for interface compatibility. Grounding jacks shall be attached to the system ground reference so that the resistance between the mating plug and the system ground reference does not exceed 1.0 ohm DC. The following grounding jacks are required:

a. Fuel nozzle ground. A ground jack shall be installed at each fuel inlet. To satisfy international agreements for interfacing with refueling hardware, the jack shall be located within 1.0 meter of the center of the fuel inlet for fuel nozzle grounding.

b. Servicing grounds. Ground jacks shall be installed at locations convenient for servicing and maintenance. For Navy and Army aircraft applications, a minimum of two grounding jacks shall be required for utility and helicopter aircraft and a minimum of four grounding jacks shall be required for other types of aircraft, in addition to those required for fueling or weapons loading or downloading.

c. Weapon grounds. Grounding jacks shall be installed at locations convenient for use in handling of weapons or other explosive devices.

Compliance shall be verified by test and inspections.

5.11.2 Servicing and maintenance equipment grounds. Servicing and maintenance equipment shall have a permanently attached grounding wire suitable for connection to earth ground. All servicing equipment that handles or processes flammable fuels, fluids, explosives, oxygen, or other potentially hazardous materials shall have a permanently attached grounding wire for connection to the system. Compliance shall be verified by inspection.

5.12 TEMPEST. National security information shall not be compromised by emanations from classified information processing equipment. Compliance shall be verified by test, analysis, inspections or a combination thereof. (NSTISSAM TEMPEST/1-92 and NACSEM 5112 provide testing methodology for verifying compliance with TEMPEST requirements.)

5.13 Emission control (EMCON). For Army applications, Navy applications, and other systems applications capable of shipboard operation, unintentional electromagnetic radiated emissions shall not exceed -110 dBm/m^2 at one nautical mile (-105 dBm/m^2 at one kilometer) in any direction from the system over the frequency range of 500 kHz to 40 GHz. Unless otherwise specified by the procuring activity, EMCON shall be activated by a single control function for aircraft. Compliance shall be verified by test and inspection.

5.14 Electronic protection (EP). For Army aircraft and Navy aircraft applications, intentional and unintentional electromagnetic radiated emissions in excess of the EMCON limits shall preclude the classification and identification of the system such that system operational performance requirements are met. Unless otherwise specified by the procuring activity, EP shall be activated by a single control function. Compliance shall be verified by test, analysis, inspections, or a combination thereof.

6. NOTES

(This section contains information of a general or explanatory nature that may be helpful, but is not mandatory.)

6.1 Intended use. This standard contains electromagnetic environmental effects requirements for systems.

6.2 Issue of DoDISS. When this standard is used in acquisition, the applicable issue of the DoDISS must be cited in the solicitation (see 2.2.1 and 2.3).

6.3 Associated Data Item Descriptions (DIDs). This standard is cited in DoD 5010.12-L, Acquisition Management Systems and Data Requirements Control List (AMSDL), as the source document for the following DIDs. When it is necessary to obtain the data, the applicable DIDs must be listed on the Contract Data Requirements List (DD Form 1423), except where the DoD Federal Acquisition Regulation Supplement exempts the requirement for a DD Form 1423.

DID Number	DID Title
DI-EMCS-81540	Electromagnetic Environmental Effects (E^3) Integration and Analysis Report
DI-EMCS-81541	Electromagnetic Environmental Effects (E^3) Verification Procedures
DI-EMCS-81542	Electromagnetic Environmental Effects (E^3) Verification Report

The above DIDs were current as of the date of this standard. The current issue of the AMSDL must be researched to ensure that only current and approved DIDs are cited on the DD Form 1423.

6.4 Tailoring guidance. Application specific criteria may be derived from operational and engineering analyses on the system being procured for use in specific environments. When analyses reveal that a requirement in this standard is not appropriate or adequate for that procurement, the requirement should be tailored and incorporated into the appropriate documentation. The appendix of this standard provides guidance for tailoring.

6.5 Supersession. The following documents have been superseded by this standard:

MIL-STD-1818A (4 October 1993)
MIL-E-6051D (7 September 1967)
MIL-B-5087B (15 October 1964)
MIL-STD-1385B (6 August 1986)

6.6 Subject term (key word) listing.

E^3
Electrical bonding
EMC
EMCON
EMI
EMP
EP
Electromagnetic compatibility
Electromagnetic environment
Electromagnetic emission
Electromagnetic interference
Electromagnetic radiation hazards
Electromagnetic susceptibility
Electronic protection
Grounding
HERF
HERO
HERP
Inter-system electromagnetic compatibility
Intra-system electromagnetic compatibility
Lightning
Multipaction
RADHAZ
System
TEMPEST

6.7 International standardization agreements. Certain provisions of this standard may be the subject of international standardization agreements. When amendment, revision, or cancellation of this standard is proposed which will modify the international agreement concerned, the preparing activity will take appropriate action through international standardization channels, including departmental standardization offices to change the agreement or make other appropriate accommodation.

6.8 Tiering. The standard is constructed to account for new DoD requirements that only first tier references are contractually binding. Each requirement paragraph begins with at least one stand-alone performance statement which does not reference other documents. Follow-on wording will sometimes reference an appropriate document which is the source of the requirement or contains additional information. The requirements of this standard can be implemented in different ways. The standard can be directly referenced in a procurement specification for a system as a source of E^3 requirements. The standard then becomes a first tier reference. Each requirement should be reviewed for applicability and possible need for tailoring. An alternate approach is to extract appropriate paragraphs from the standard, tailor them as necessary, and insert them directly into the procurement specification. Under this approach, direct reference can be made to other documents, including the text of this standard. These references are then first tier and become contractual.

6.9 Technical points of contact. Requests for additional information or assistance on this standard can be obtained from the following:

Air Force
ASC/ENA, Bldg. 560
2530 Loop Road West
Wright Patterson AFB, OH 45433-7101
DSN 785-5078, Commercial (937) 255-5078

Army
Director, AMSAA
AMXSY-RE
APG, MD 21005-5071
DSN 298-6994, Commercial (410) 278-6994

Navy
Commander, Naval Air Systems Command
NAVAIR 4.1.7
Arlington, VA 22243-5120
DSN 664-6060, Ext. 5651, Commercial (703) 604-6060, Ext. 5651

Any information relating to Government contracts must be obtained through contracting officers.

APPENDIX

MIL-STD-464
APPLICATION GUIDE

CONTENTS

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TABLES

FIGURES

A1 SCOPE

A1.1 Scope. This appendix provides background information for each requirement in the main body of the standard. The information includes rationale for each requirement, guidance on applying the requirement, and lessons learned related to the requirement. This information should help users understand the intent behind the requirements and adapt them as necessary for a particular application.

A2 APPLICABLE DOCUMENTS

A2.1 Government documents

A2.1.1 Specifications, standards, and handbooks. The following specifications, standards, and handbooks are referenced in this appendix and form a part of this document to the extent specified herein.

SPECIFICATIONS

Military

MIL-I-23659	Initiator, Electric, General Design Specification
MIL-C-83413	Connectors and Assemblies, Electrical, Aircraft Grounding, General
MIL-W-83575	Wiring Harness, Space Vehicle, Design and Testing

STANDARDS

Military

MIL-STD-188-124	Grounding, Bonding and Shielding for Common Long Haul/Tactical Communications Systems Including Ground Based Communication-Electronics Facilities and Equipments
MIL-STD-188-125	High Altitude Electromagnetic Pulse (HEMP) Protection for Ground-Based C^4I Facilities Performing Critical, Time-Urgent Missions
MIL-STD-331	Fuze and Fuze Components, Environmental and Performance Tests for
MIL-STD-449	Radio Frequency Spectrum Characteristics, Measurement of
MIL-STD-461	Requirements for the Control of Electromagnetic Interference Emissions and Susceptibility
MIL-STD-462	Measurement of Electromagnetic Interference Characteristics
MIL-STD-469	Radar Engineering Design Requirements, Electromagnetic Compatibility
MIL-STD-704	Aircraft Electric Power Characteristics
MIL-STD-1310	Shipboard Bonding, Grounding, and Other Techniques for

	Electromagnetic Compatibility and Safety
MIL-STD-1399-070	Interface Standard for Shipboard Systems, DC Magnetic Field Environment
MIL-STD-1399-300	Interface Standard for Shipboard Systems, Section 300, Electric Power, Alternating Current
MIL-STD-1542	Electromagnetic Compatibility and Grounding Requirements for Space System Facilities
MIL-STD-1568	Materials and Processes for Corrosion Prevention and Control in Aerospace Weapon Systems
MIL-STD-1576	Electroexplosive Subsystem Safety Requirements and Test Methods for Space Systems
MIL-STD-1605	Procedures for Conducting a Shipboard Electromagnetic Interference (EMI) Survey (Surface Ships)
MIL-STD-1680 (SH)	Installation Criteria for Shipboard Secure Electrical Information Processing Systems
MIL-STD-2169	High Altitude Electromagnetic Pulse Environment

HANDBOOKS

MIL-HDBK-235	Electromagnetic (Radiated) Environment Considerations for Design and Procurement of Electrical and Electronic Equipment, Subsystems and Systems
MIL-HDBK-237	Electromagnetic Compatibility Management Guide for Platforms, Systems, and Equipment
MIL-HDBK-419	Grounding, Bonding, and Shielding for Electronic Equipments and Facilities
MIL-HDBK-423	High-Altitude Electromagnetic Pulse (HEMP) Protection for Fixed and Transportable Ground-Based Facilities
MIL-HDBK-454	Electronic Equipment, General Guidelines for
MIL-HDBK-274	Electrical Grounding for Aircraft Grounding

(Unless otherwise indicated, copies of federal and military specifications, standards, and handbooks are available from the Standardization Documents Order Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094. Application for copies of MIL-STD-2169 should be addressed with a need-to-know to: Defense Special Weapons Agency, Electronics Technology Division, 6801 Telegraph Road, Alexandria, VA 22310-3398.)

A2.1.2 Other Government documents, drawings, and publications. The following other Government documents are referenced in this appendix.

Air Force

AFAPL-TR-78-56	Static Electricity Hazards in Aircraft Fuel Systems
AFAPL-TR-78-89	Factors Affecting Electrostatic Hazards
AFWL-TR-85-113	Guidelines for Reducing EMP Induced Stresses in Aircraft
LA-5201-MS	Response of Airborne Electroexplosive Devices to Electromagnetic Radiation (AD 912 599)

R-3046-AF	Techniques for the Analysis of Spectral and Orbital Congestion in Space Systems (DTIC No. ADA140841)
TO 00-25-172	Ground Servicing of Aircraft and Static Grounding/Bonding
TO 31Z-10-4	Electromagnetic Radiation Hazards

Department of Defense (DoD)

DoDI 6055.11	Protection of DoD Personnel from Exposure to Radiofrequency Radiation and Military Exempt Lasers
DoDD 4650.1	Management and Use of the Radio Frequency Spectrum
DoDD 5200.19	Control of Compromising Emanations (Classified)

Federal Aviation Administration (FAA)

AC 20-53	Protection of Aircraft Fuel Systems Against Fuel Vapor Ignition Due to Lightning
AC 20-136	Protection of Aircraft Electrical/Electronic Systems Against the Indirect Effects of Lightning
DOT/FAA/CT-89/2	Aircraft Lightning Handbook
DOT/FAA/CT-86/40	Aircraft Electromagnetic Compatibility

NASA

TP2361	Design Guidelines for Assessing and Controlling Spacecraft Charging Effects
TR 32-1500	Final Report on RF Voltage Breakdown in Coaxial Transmission Lines

Navy

NAWCWPNS TS 92-78	Electronic Warfare and Radar Systems Engineering Handbook
NAVSEA OP 3565/ NAVAIR 16-1-529/ NAVELEX 0967-LP-624-6010	Electromagnetic Radiation Hazards
OD 30393	Design Principles and Practices for Controlling Hazards of Electromagnetic Radiation to Ordnance (HERO DESIGN GUIDE)

Publications

NACSEM 5112	NONSTOP Evaluation Techniques
NSTISSAM TEMPEST/1-92	Compromising Emanations Laboratory Test Requirements, Electromagnetics
NSTISSAM TEMPEST/1-93	Compromising Emanations Field Test Evaluations

NSTISSAM TEMPEST/2-95	Red/Black Installation Guidelines
NTIA	Manual of Regulations and Procedures for Federal Radio Frequency Management
OMB Circular A-11	Preparation and Submission of Budget Estimates

(Copies of FAA publications and military technical reports are available from National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22161 or the Defense Technical Information Center (DTIC), Bldg. 5, Cameron Station, Alexandria, VA 22304-6145. Air Force Technical Orders are available from Oklahoma City Air Logistics Center (OC-ALC/MMEDT), Tinker AFB, OK 73145-5990. Copies of DoD documents are available from the Standardization Documents Order Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094. Copies of NASA documents are available from NASA Industrial Application Center/USC, 3716 South Hope St. # 200, Los Angeles, CA 90007. Copies of NAVSEA documents available from Commanding Officer, Naval Surface Warfare Center, Port Hueneme Division, Naval Sea Data Support Activity (Code 5700), Department of the Navy, Port Hueneme, CA 93043. Copies of NACSEM, NSTISSAM, and NSA documents are available only through the procuring activity.)

A2.2 Non-Government publications. The following non-Government documents form a part of this standard to the extent specified herein.

International Organization for Standardization

ISO 46	Aircraft - Fuel Nozzle Grounding Plugs and Sockets

(Application for copies should be addressed to ISO, International Organization for Standardization, 3 rue de Varembe, 1211 Geneve 20, Geneve, Switzerland; phone 41 22 734 0150)

Franklin Applied Physics

F-C2560	RF Evaluation of the Single Bridgewire Apollo Standard Initiator
M-C2210-1	Monograph on Computation of RF Hazards

(Application for copies should be addressed to Franklin Applied Physics, P.O. Box 313, Oaks, PA 19456)

National Fire Protection Association (NFPA)

70	National Electrical Code
780	Lightning Protection Code

(Application for copies of the Code should be addressed to the National Fire Protection Association, Batterymarch Park, Quincy, MA 02269-9101.)

North Atlantic Treaty Organization (NATO)

ANEP 45	Electro-Magnetic Compatibility (EMC) in Glass Reinforced Plastic (GRP) Vessels

(Application for copies should be addressed to Central US Registry, The Pentagon, Room 1B889, Washington, DC 20310-3072)

RTCA

DO-160	Environmental Conditions and Test Procedures for Airborne Equipment

(Application for copies of this standard should be addressed to RTCA, 1425 K Street NW, Washington, DC 20005; phone (202) 682-0266.)

Society of Automotive Engineers, Inc.

AE4L-87-3	Protection of Aircraft Electrical/Electronic Systems Against the Indirect Effects of Lightning
ARP 1870	Aerospace Systems Electrical Bonding and Grounding for Electromagnetic Compatibility and Safety
ARP 4242	Electromagnetic Compatibility Control Requirements, Systems

(Application for copies should be addressed to the Society of Automotive Engineers Inc., 400 Commonwealth Drive, Warrendale, PA 15096; phone (412) 776-4841.)

Statistical Research Group

AMP Report No. 101-1R SRG-P, No. 40	Statistical Analysis for a New Procedure in Sensitivity Experiments (ATI-34558)

(Application for copies should be addressed to the Defense Technical Information Center (DTIC), Bldg. 5, Cameron Station, Alexandria, VA 22304-6145)

A3. ACRONYMS. The acronyms used in this appendix are defined as follows.

AAPG	antenna inter-antenna propagation with graphics
AGC	automatic gain control
AM	amplitude modulation
AMITS	air management information tracking system
ASEMICAP	air systems EMI corrective action program
BIT	built-in test
C^3I	command, control, communications, and intelligence

C^4I	command, control, communications, computers, and intelligence
CTTA	certified TEMPEST technical authority
CW	continuous wave
E^3	electromagnetic environmental effects
ECCM	electronic counter counter-measures
ECM	electronic counter-measures
EID	electrically initiated device
EM	electromagnetic
EMC	electromagnetic compatibility
EMCON	emission control
EME	electromagnetic environment
EMI	electromagnetic interference
EMP	electromagnetic pulse
EMRADHAZ	electromagnetic radiation hazards
EMV	electromagnetic vulnerability
EP	electronic protect
ESD	electrostatic discharge
GPS	global positioning system
HEMP	high altitude electromagnetic pulse
HERF	hazards of electromagnetic radiation to fuel
HERO	hazards of electromagnetic radiation to ordnance
HERP	hazards of electromagnetic radiation to personnel
HIRF	high intensity radiated fields
IMI	intermodulation interference
MHD	magnetohydrodynamic
MNFS	maximum no-fire stimulus
NDI	non-developmental item
POR	point of regulation
p-static	precipitation static
RF	radio frequency
SEMCIP	ship EMC improvement program
TWT	traveling wave tube

A4. GENERAL REQUIREMENTS AND VERIFICATION. In this section, the requirements from the main body are repeated (printed in italics) and are then followed by rationale, guidance, and lessons learned for each interface requirement and rationale, guidance, and lessons learned for each verification requirement. Interface and verification requirement discussions are treated separately because they address different issues. Tables and figures associated with the requirements from the main body are also repeated with their same alphanumeric designations. Tables and figures which are unique to the appendix have alphanumeric designations which are preceded by an “A”.

A4.1 General. *The system shall be electromagnetically compatible among all subsystems and equipment within the system and with environments caused by electromagnetic effects external to the system. Verification shall be accomplished as specified herein on production representative systems. Safety critical functions shall be verified to be electromagnetically compatible within* *the system and with external environments prior to use in those environments. Verification shall address all life cycle aspects of the system, including (as applicable) normal in-service operation, checkout, storage, transportation, handling, packaging, loading/unloading, launch, and the normal operating procedures associated with each aspect.*

Requirement Rationale (A4.1): The E^3 area addresses a number of interfacing issues with environments both external to the system and within the system. External to the system are electromagnetic effects such as lightning, EMP and man-made RF transmissions. Internal to the system are electromagnetic effects such as electronic noise emissions, self-generated RF transmissions from antennas, and cross-coupling of electrical currents. Systems today are complex from a materials usage and electronics standpoint. Many materials being used are non-metallic and have unique electromagnetic properties which require careful consideration. Electronics performing critical functions are common. Wide use of RF transmitters, sensitive receivers, other sensors, and additional electronics creates a potential for problems within the system and from external influences. Increasing use of commercial equipment in unique military operational environments poses special interface considerations. Each system must be compatible with itself, other systems, and external environments to ensure required performance and to prevent costly redesigns for resolution of problems.

Requirement Guidance (A4.1): The system and all associated subsystems and equipment, including ordnance, need to achieve system compatibility. Every effort needs to be made to meet these requirements during initial design rather than on an after-the-fact basis. System E^3 Integration and Analysis Reports are used to aid in technical management of programs. These reports describe requirement flowdown from this standard and specific design measures being implemented to meet the requirements of this standard. The other requirements of this standard address specific aspects of the E^3 control area. Additional guidance on EMC can be found in MIL-HDBK-237, DOT/FAA/CT-86/40, SAE ARP 4242, and NATO ANEP 45.

An overall integrated EMC design and verification approach for the system must be established. Based on system-level architecture, appropriate hardening requirements are allocated between system design features and subsystems and equipment hardness. Transfer functions from system-level environments to stresses at the subsystem and equipment-level are determined and appropriate electromagnetic interference controls are imposed.

An E^3 integration approach can be organized into five activities:

a. Establish the external threat environment against which the system is required to demonstrate compliance of immunity. The external environments (EME, lightning and EMP) to which the system should be designed and verified are addressed in other sections of this appendix.

b. Identify the system electrical and electronic equipment performing functions required for operation during application of the external threat. Normally all functions essential for completing the missions are protected against the external threats.

c. Establish the internal environment caused by external electromagnetic effects for each installed equipment. All of the environments external to the system specified in this standard cause related environments internal to the system. The level of this internal environment will be the result of many factors such as structural details, penetration of apertures and seams, and system and cable resonances. The internal environment for each threat should be established by analysis, similarity to previously tested systems, or testing. The internal environment is usually expressed as the level of electrical current stresses appearing at the interface to the equipment or electromagnetic field quantities. These internal stresses are typically associated with standardized requirements for equipment (for example, MIL-STD-461). Trade-offs need to be made of the degree of hardening to be implemented at the system-level (such as shielded volumes or overbraiding on interconnecting wiring) versus equipment-level (more stringent electromagnetic interference requirements) to establish the most effective approach from performance and cost standpoints.

d. Design the system and equipment protection. System features are then designed as necessary to control the internal environment (including margin considerations) to levels determined from the trade-off studies and appropriate requirements are imposed on the electrical and electronic equipment. The equipment immunity levels must be above the internal environments by necessary margins to account for criticality of the equipment, manufacturing tolerances, and uncertainties in verification. Normally there are design and test requirements in MIL-STD-461 and MIL-STD-462 applicable for each of the external environments, but they may need modification for the particular system application. For example, external environment may result in internal environments above the susceptibility level specified in MIL-STD-461. If so, the limit must be tailored for the particular system, alternative requirements must be imposed or the internal environment must be reduced to an acceptable level. The system E^3 design must be viable throughout the system life cycle. This aspect requires an awareness of 1) proper application of corrosion control provisions and 2) issues related to maintenance actions that may affect EMC, such as ensuring electrical bonding provisions are not degraded, maintaining surface treatments in place for E^3 control, and considering exposure of electronics to EMEs when access panels are open.

e. Verify the protection adequacy. The system and equipment E^3 protection design must be verified as meeting contractual requirements. Verification of the adequacy of the protection design includes demonstrating that the actual levels of the internal environments appearing at the equipment interfaces and enclosures do not exceed the qualification test levels of the equipment for each environment by required margins. All electronic and electrical equipments must have been qualified to their appropriate specification level. Systems-level testing is normally required to minimize the required-margin demonstration. Analysis may be acceptable under some conditions; however, the required margins will typically be larger.

These verification activities need to be documented in detail in verification procedures and verification reports, as applicable. Section 6.3 of the main body provides data item descriptions for documents that are suitable for this purpose.

Requirement Lessons Learned (A4.1): The early implementation of E^3 requirements have been instrumental in preventing problems on previous programs. Evolving system designs regarding changing materials and increasing criticality of electronics demand that effective electromagnetic effects controls be implemented.

It is important that all external environments be treated in a single unified approach. Duplication of efforts in different disciplines have occurred in the past. For example, hardening to electromagnetic pulse and lightning-induced transients have been addressed independently rather than as a common threat with different protection measures being implemented for each. This situation is apparently due in part to organizational structures at contractor facilities which place responsibility in different offices for each of the threats.

Verification Rationale (A4.1): Each separate requirement must be verified. The developing activity must demonstrate that the system, subsystem and equipment operate compatibly with the external environments (EME, lightning, and EMP) contained in the system requirements and in accordance with the system contract Statement of Work. The developing activity must also assign verification responsibility to associate contractors for their supplied systems and subsystems to demonstrate compliance with E^3 requirements.

Verification Guidance (A4.1): Most of the requirements in this standard are verified at the system-level. Compliance for some requirements is verified at the subsystem, equipment, or component level, such as electromagnetic interference requirements on a subsystem or lightning certification of an airframe component.

The selection of test, analysis, or inspection or some combination to demonstrate a particular requirement is generally dependent on the degree of confidence in the results of the particular method, technical appropriateness, associated costs, and availability of assets. Some of the requirements included in this standard specify the method to be used. For example, verification of subsystem and equipment-level electromagnetic interference requirements must be demonstrated by test, because analysis tools are not available which will produce credible results.

Analysis and testing often supplement each other. Prior to the availability of hardware, analysis will often be the primary tool being used to ensure that the design incorporates adequate provisions. Testing may then be oriented toward validating the accuracy and appropriateness of the models used. If model confidence is high, testing may then be limited. For example, design of an aircraft for protection against EMP or the indirect effects of lightning has to rely heavily on analysis.

E^3 requirements need to be verified through an incremental verification process. "Incremental" implies that verification of compliance with E^3 requirements is a continuing process of building an argument (audit trail) throughout development that the design satisfies the imposed performance requirements. Initial engineering design must be based on analysis and models. As hardware becomes available, testing of components of the subsystem can be used to validate and supplement the analysis and models. The design evolves as better information is generated. When the system is actually produced, inspection, final testing, and follow-on analysis complete the incremental verification process. It is important to note that testing is often necessary to obtain information that may not be amenable to determination by analysis. However, testing also is often used to determine a few data points with respect to a particular interface requirement with analysis (and associated simulations) filling in the total picture. It should be noted that the guidance sections for individual E^3 requirements specified in other sections below generally treat the predominant methods for final verification rather than dealing with the overall philosophy described in this section.

The following list provides guidance on issues which should be addressed for E^3 verification:

a. Systems used for verification should be production configuration, preferably the first article.

b. The system should be up-to-date with respect to all approved engineering change proposals (both hardware and software).

c. Electromagnetic interference qualification should be completed on subsystems and equipment.

d. Subsystems and equipment should be placed in modes of operation that will maximize potential indication of interference or susceptibility, consistent with system operational performance requirements.

e. Any external electrical power used for system operation should conform to the power quality standard of the system.

f. Any anomalies found should be evaluated to determine whether they are truly an E^3 issue or some other type of malfunction or response.

g. Any system modifications resulting from verification efforts should be validated for effectiveness after they have been engineered.

h. Margins need to be demonstrated wherever they are applicable.

Verification Lessons Learned (A4.1): Historically, failure to adequately verify system performance in an operational EME has resulted in costly delays during system development, mission aborts, and reduced system and equipment operational effectiveness. It is important that assets required for verification of E^3 requirements be identified early in the program to ensure their availability when needed.

A5. DETAILED REQUIREMENTS

A5.1 Margins. *Margins shall be provided based on system operational performance requirements, tolerances in system hardware, and uncertainties involved in verification of system-level design requirements. Safety critical and mission critical system functions shall have a margin of at least 6 dB. Ordnance shall have a margin of at least 16.5 dB of maximum no-fire stimulus (MNFS) for safety assurances and 6 dB of MNFS for other applications. Compliance shall be verified by test, analysis, or a combination thereof. Instrumentation installed in system components during testing for margins shall capture the maximum system response and shall not adversely affect the normal response characteristics of the component. When environment simulations below specified levels are used, instrumentation responses may be extrapolated to the full environment for components with linear responses (such as hot bridgewire EIDs). When the response is below instrumentation sensitivity, the instrumentation sensitivity shall be used as the basis for extrapolation. For components with non-linear responses (such as semiconductor bridge EIDs), no extrapolation is permitted.*

Requirement Rationale (A5.1): Variability exists in system hardware from factors such as differences in cable harness routing and makeup, adequacy of shield terminations, conductivity of finishes on surfaces for electrical bonding, component differences in electronics boxes, and degradation with aging and maintenance. Margins must be included in the design to account for these types of variabilities. In addition, uncertainties are present in the verification process due to the verification method employed, limitations in environment simulation, and accuracy of measured data. The proper application of margins in system and subsystem design provides confidence that all production systems will perform satisfactorily in the operational E^3 environments.

Requirement Guidance (A5.1): Margins are generally applicable to all environments external to the system, including lightning (only indirect effects), inter-system EMC, and EMP; to aspects of intra-system EMC associated with any type of coupling to explosive circuits; and with effects caused by RF transmissions. For Navy and Army aircraft, margins are applied to other aspects of intra-system EMC. Generally, margins are not applicable to the section 5.2.3 powerline transient requirement. Verification has been limited to analysis for the other aspects where testing is impractical.

Margins need to be viewed from the proper perspective. The use of margins simply recognizes that there is variability in manufacturing and that requirement verification has uncertainties. The margin ensures that every produced system will meet requirements, not just the particular one undergoing a selected verification technique. Smaller margins are appropriate for situations where production processes are under tighter controls or more accurate and thorough verification techniques are used. Smaller margins are also appropriate if many production systems undergo the same verification process, since the production variability issue is being addressed. Margins are not an increase in the basic defined levels for the various electromagnetic environments. The most common technique is to verify that electromagnetic and electrical stresses induced internal to the system by external environments are below equipment strength by at least the margin. While margins can sometimes be demonstrated by performing verification at a level in excess of the defined requirement, the intent of the margin is not to increase the requirement.

The 16.5 dB margin specified for safety assurance for ordnance is derived from the criterion in MIL-STD-1385 (superseded by this document) that the maximum allowable induced level for electrically initiated devices (EIDs) in required environments is 15% of the maximum no-fire current. The ratio of no-fire to allowable currents in decibels is 20 log (0.15) or - 16.5 dB. The requirement is expressed in decibels so that the requirement can be applied to ordnance designs which do not use conventional hot bridgewire EIDs and where no-fire current may be meaningless. MIL-STD-1385 also indicated a 6 dB margin for ordnance when there are consequences other than safety.

Hot bridgewire EIDs with a one amp/one watt MNFS are often used in ordnance applications to help in meeting safety requirements. As an alternative to using large sample sizes to demonstrate that the statistical criteria contained in the definition of MNFS (no more than 0.1% firing with a confidence level of 95%) is met, the methods of MIL-I-23659 can be used to define a one amp/one watt MNFS.

MNFS values for ordnance are normally specified by manufacturers in terms such as DC currents or energy. Margins are often demonstrated with respect to observed effects (such as the temperature rise of bridgewires) during the application of electromagnetic environments relative to effects observed by applying a stimulus level in the form under which the MNFS is defined (such as DC current level related to the required margin). The space community has elected to use MNFS levels determined using RF rather than DC. This approach is based on Franklin Institute studies, such as report F-C2560. Outside of the space community, the use of DC levels has provided successful results.

Margins are closely linked to both design and verification since the planned verification methodology influences the size of the margin and the resulting impact on the required robustness of the design. The specific margin assigned for a particular design and environment is an engineering judgment. If the margin is too large, then penalties in weight and cost can be inflicted on the design. If the margin is too small, then the likelihood of a undesirable system response becomes unacceptably high.

The size of the margin assigned is inversely proportional to the inherent accuracy of the verification method employed. One method of verifying lightning protection is to expose an operational aircraft to a simulated severe lightning encounter (most severe flashes with worst case attachment points). With this relatively accurate method of verification, a smaller overall margin should be required. Another method of verifying lightning protection is the use of low-level pulsed or continuous-wave (CW) testing with extrapolation of measured induced levels on electrical cabling to a full scale strike. These levels are then either applied to the cables at the system level or compared to laboratory data. This type of approach would typically require an overall margin of 6 dB. Similar margins may be appropriate for pure analysis approaches which produce results which have been shown by previous testing to be consistently conservative for the particular type of system being evaluated.

The least accurate verification method is the use of an analysis which has not been previously verified as yielding “accurate” results for the system type of interest. The term “previously verified" in this case means that the analysis is based on accepted principles (such as previously documented in E^3 handbooks) but the particular system configuration presented for certification has not been previously tested to verify the accuracy of the analysis. For this case, margins as large as 30 dB are not unrealistic.

For most approaches, margins typically fall in the range of 6 to 20 dB. For equipment that is not classified as safety critical, mission critical, or ordnance, it may be desirable to use a reduced (possibly zero) margin to conserve program resources.

Requirement Lessons Learned (A5.1): The use of margins in verifying intra-system EMC requirements among subsystems by test has been attempted in the past; however, this practice has largely been abandoned except for electroexplosive circuits. A basic difficulty existed in the lack of available techniques to evaluate how close a circuit is to being upset or degraded. With the numerous circuits on most platforms, it can be a formidable task to evaluate all circuits. One technique that has been used is to identify the circuits through analysis which are potentially the most susceptible. The intentional signal being transmitted across the electrical interface is reduced in amplitude the required number of dB to decrease the relative level of the intentional signal to whatever interference is present. However, there is some controversy in this type of testing since the receiving circuit does not see its normal operating level. Margins for EIDs have been commonly demonstrated using techniques such as electro-optics, infrared, current probes, thermocouples, RF detectors, and temperature sensitive waxes.

Verification Rationale (A5.1): To obtain confidence that the system will perform effectively in the various environments, margins must be verified. In addition to variability in system hardware, test and analysis involve uncertainties which must be taken into account when establishing whether a system has met its design requirements. These uncertainties include instrumentation tolerances, measurement errors, and simulator deficiencies (such as inadequate spectral coverage).

Verification of margins for space and launch vehicles is essential since these items are costly and must meet performance the first and only time. There are no on-orbit repairs.

Verification Guidance (A5.1): Some uncertainties, such as system hardware variations or instrumentation errors, may be known prior to the verification effort. Other uncertainties must be evaluated at the time of a test or as information becomes available to substantiate an analysis. Margins must be considered early in the program so that they may be included in the design. It is apparent that better verification techniques can result in leaner designs, since uncertainties are smaller. Caution must be exercised in establishing margins so that the possible lack of reliable or accurate verification techniques does not unduly burden the design.

During an E^3 test, the contribution to uncertainties from the test are either errors or variations. The errors fall into categories of measurement, extrapolation (simulation), and repeatability. Variations are caused by various issues such as system orientation with respect to the incident field, polarization of the incident field, and different system configurations (such as power on/off, refuel, ground alert). The contributions of errors and variations are combined for margin determination. They can be directly added; however, this approach will tend to produce an overly conservative answer. The more common approach is to combine them using the root-sum-square.

Verification Lessons Learned (A5.1): An example of margin demonstration used during verification of lightning indirect effects and electromagnetic pulse protection is the demonstration that the electrical current levels induced in system electrical cables by the particular environment are less than the demonstrated equipment hardness at least by the margin. This verification is generally accomplished by a combination of tests and analyses. The equipment hardness level is generally demonstrated in the laboratory during testing in accordance with MIL-STD-462. Testing can also be performed on individual equipment items at the system-level. There are some concerns with induced transient waveforms determined at the system-level being different than those used during equipment-level testing. Analysis techniques are available for waveform comparison such as norm attributes. Test techniques are available to inject measured current waveforms into electrical cables at amplified levels during a system-level test.

A5.2 Intra-system electromagnetic compatibility (EMC). *The system shall be electromagnetically compatible within itself such that system operational performance requirements are met. Compliance shall be verified by system-level test, analysis, or a combination thereof.*

Requirement Rationale (A5.2): It is essential within a system that the subsystems and equipment be capable of providing full performance in conjunction with other subsystems and equipment which are required to operate concurrently. EMI generated by a subsystem or other subsystems and equipment must not degrade the overall system effectiveness.

Electromagnetic compatibility among antenna-connected subsystems (termed RF compatibility on some programs) is an essential element of system performance. Inability of an antenna-connected subsystem to properly receive intentional signals can significantly affect mission effectiveness. Achieving compatibility requires careful, strategic planning for the placement of receiver and transmitter antennas on the system and on the interoperability of the subsystems

Requirement Guidance (A5.2): Intra-system EMC is the most basic element of E^3 concerns. The various equipment and subsystems are designed and integrated to coexist and to provide the operational performance required by the user. However, varying degrees of functionality are necessary depending upon the operational requirements of individual items during particular missions. Certain equipment may not need to be exercised at the time of operation of other equipment. For this situation, intra-system compatibility requirements do not necessarily apply. The procuring activity and system user should be consulted to determine the required functionality. An example of these circumstances is that it is unlikely that an aircraft instrument landing system needs to be compatible with a radiating electronic warfare jamming subsystem during precision approaches. However, they need to be compatible during other operations such as when BIT is exercised.

Requirement Lessons Learned (A5.2): When appropriate controls are implemented in system design, such as hardening, EMI requirements on subsystems and equipment, and good grounding and bonding practices, there are relatively few intra-system EMC problems found. Most problems that are found involve antenna-connected transmitters and receivers. Receiver performance has been degraded by broadband thermal noise, harmonics, and spurious outputs coupled antenna-to-antenna from transmitters. Microprocessor clock harmonics radiating from system cabling and degrading receivers have been another common problem. Electromagnetic fields radiated from onboard antennas have affected a variety of subsystems on platforms. Typical non-antenna-related problems have been transients coupled cable-to-cable from unsuppressed inductive devices and power frequencies coupling into audio interphone and video signal lines. Problems due to cable-to-cable coupling of steady state noise and direct conduction of transient or steady state noise are usually identified and resolved early in the development of a system.

Generation of broadband EMI on ships from electrical arcing has been a common source of degradation of antenna-connected receivers and must be controlled. Sources of the arcing have been brush noise from electrical machinery and induced voltages and currents between metallic items from antenna transmissions. Intermittent contact of the metallic items due to wind or ship motion is a contributor. MIL-STD-1605 provides guidance on controlling and locating sources of broadband EMI.

An effective software tool for antenna-to-antenna coupling analysis on aircraft available through the Joint Spectrum Center is AAPG (Antenna inter-Antenna Propagation with Graphics). AAPG models the aircraft with a combination of cylinders or truncated cylinders and flat plates to estimate isolation between antennas as a function of free-space loss and shading by the fuselage and wings. Isolation in conjunction with the other parameters allows a first estimate of interference levels between subsystems. AAPG considers all signals as continuous; the program does not account for the effects of pulsed RF. Also, blanking is not considered in AAPG. Limitations of any analysis program must be considered when using the results to draw conclusions.

A common problem in systems occurs when the system uses both ECM (electronic countermeasures) and radar equipment operating at overlapping frequencies. The following measures may be helpful to provide RF compatibility between these types of subsystems: blanking, pulse tagging, utilization of coherent processing dead time, band splitting, and digital feature extraction. A blanking matrix is commonly used to depict the relationship between source and victim pairs.

A relatively new technique to attenuate an interfering signal at a receiver is frequency cancellation. This technique samples the interfering signal separate from the receiver's antenna, performs a phase inversion, and adds the result to the overall received signal. Thus, the interfering signal can be reduced substantially leaving the desired received signal essentially unaffected. The hardware to perform this action is complex and expensive.

Verification Rationale (A5.2): Verification of intra-system electromagnetic compatibility through testing supported by analysis is the most basic element of demonstrating that E^3 design efforts have been successful.

Verification of RF compatibility by test is essential to ensure an adequate design which is free from the degradation caused by antenna-to-antenna coupled interference. Prior analysis and equipment-level testing are necessary to assess potential problems and to allow sufficient time for fixing subsystem problems.

Verification Guidance (A5.2): Although analysis is an essential part of the early stages of designing or modifying a system, testing is the only truly accurate way of knowing that a design meets intra-system EMC requirements. An anechoic chamber is usually required for system-level testing to minimize reflections and ambient interference that can degrade the accuracy of the testing and to evaluate modes of operation that are reserved for war or are classified.

The following list provides guidance on issues which should be addressed for intra-system EMC testing:

a. Potential interference source versus victim pairs should be systematically evaluated by exercising the subsystems and equipment onboard the system through their various modes and functions while monitoring the remaining items for degradation. Both one source versus a victim and multiple sources versus a victim conditions need to be considered.

b. A frequency selection plan should be developed for exercising antenna-connected transmitters and receivers. This plan should include:

1). Predicable interactions between transmitters and receivers such as transmitter harmonics, intermodulation products, other spurious responses (such as image frequencies), and cross modulation. The acceptability of certain types of responses will be system dependent.

2). Evaluation of transmitters and receivers across their entire operating frequency range, including emergency frequencies.

3). Evaluation of electromagnetic interference emission and susceptibility issues with individual subsystems.

c. Margins should be demonstrated for explosive subsystems and other relevant subsystems.

d. Operational field evaluation of system responses found in the laboratory environment should be performed (such as flight testing of an aircraft to assess responses found during testing on the ground).

e. Testing should be conducted in an area where the electromagnetic environment does not affect the validity of the test results. The most troublesome aspect of the environment is usually dense utilization of the frequency spectrum, which can hamper efforts to evaluate the performance of antenna-connected receivers with respect to noise emissions of other equipment installed in the system.

f. Testing should include all relevant external system hardware such as weapons, stores, provisioned equipment (items installed in the system by the user), and support equipment.

g. It should be verified that any external electrical power used for system operation conforms with the power quality standard of the system.

Operational testing of systems often begins before a thorough intra-system electromagnetic compatibility test is performed. Also, the system used for initial testing is rarely in a production configuration. The system typically will contain test instrumentation and will be lacking some production electronics. This testing must include the exercising and evaluation of all functions that can affect safety. It is essential that aircraft safety-of-flight testing be done to satisfy safety concerns prior to first flight and any flight thereafter where major electrical and electronic changes are introduced.

A common issue in intra-system EMC verification is the use of instrumentation during the test. The most common approach is to monitor subsystem performance through visual and aural displays and outputs. It is usually undesirable to modify cabling and electronics to monitor signals to assess subsystem performance, since these modifications may change subsystem responses and introduce additional coupling paths. However, there are some areas where instrumentation is important. Demonstration of margins for critical areas normally requires some type of monitoring. For example, EIDs require monitoring for assessment of margins.

Some antenna-connected receivers, such as airborne instrument landing systems and identification of friend or foe, require a baseline input signal (set at required performance levels) for degradation to be effectively evaluated. Other equipment which transmits energy and evaluates the return signal, such as radars or radar altimeters, need an actual or simulated return signal to be thoroughly assessed for potential effects.

The need to evaluate antenna-connected receivers across their operating ranges is important for proper assessment. It has been common in the past to check a few channels of a receiver and conclude that there was no interference. This practice was not unreasonable in the past when much of the potential interference was broadband in nature, such as brush noise from motors. However, with the waveforms associated with modern circuitry such as microprocessor clocks and power supply choppers, the greatest chance for problems is for narrowband spectral components of these signals to interfere with the receivers. Therefore, it is common practice to monitor all antenna-connected outputs with spectrum analysis equipment during an intra-system electromagnetic compatibility test. Analysis of received levels is necessary to determine the potential for degradation of a particular receiver.

Output characteristics of spread spectrum transmitters present unique technical issues which need to be addressed to achieve EMC.

RF compatibility between antenna-connected receivers is an element of intra-system electromagnetic compatibility and demonstration of compliance with that requirement needs to be integrated with these efforts. Any blanking techniques required for EMC should be included.

Verification Lessons Learned (A5.2): Performance degradation of antenna-connected communication receivers cannot be effectively assessed by simply listening to open channels as has been done commonly in the past. Squelch break has often been used as the criteria for failure. There are number of problems with this technique.

The most common receiver degradation being experienced is from microprocessor clock harmonics radiating from cabling. These signals are narrowband and stable in frequency. Considering a receiver designed to receive amplitude modulated (AM) signals, there are several responses that may be observed as discussed below. Similar analysis is applicable to other type receivers.

If an intentional signal above the squelch is present, the type of degradation is dependent on the location of the interfering signal with respect to the carrier. If the interfering signal is within a few hundred hertz of the carrier, the main effect will probably be a change in the automatic gain control (AGC) level of the receiver. If the interfering signal is far enough from the carrier to compete with the sideband energy, much more serious degradation can occur. This condition gives the best example of why squelch break is not an adequate failure criterion. AM receivers are typically evaluated for required performance using a 30%-AM, 1-kHz tone which is considered to have the same intelligibility for a listener as typical 80%-AM voice modulation. The total power in the sidebands is approximately 13 dB below the level of the carrier. Receiver specifications also typically require 10 dB (signal plus noise)-to-noise ratios during sensitivity demonstrations. Therefore, for an interfering signal which competes with the sidebands not to interfere with receiver performance, it must be approximately 23 dB below the carrier. An impact of this conclusion is that an interfering signal which is well below squelch break can cause significant range degradation in a receiver. If squelch break represents the true sensitivity required for mission performance, an interfering signal just below squelch break can cause over a 90% loss in potential range.

If no intentional signal is present and there is insignificant AM on the clock harmonic, the main result is a quieting of the receiver audio output due to AGC action. To an observer, this effect might actually appear to be an improvement in receiver performance. If some AM is present at audio passband frequencies, a signal will be apparent that is dependent on the depth of the AM; however, the degree of receiver degradation cannot be effectively assessed since it is masked by the AGC.

Two acceptable methods of assessing degradation are apparent. A 30% AM signal can be radiated at each channel of interest at an induced level at the receiver which corresponds to the minimum required performance. Changes in intelligibility can be assessed with and without the interference present. Also, the level of the signal source can be varied and the resultant effects evaluated. Due to the large number of channels on many receivers (UHF receivers (225 - 400 MHz) typically have 7000 channels), this technique may often not be practical. An increasingly popular approach is to monitor antenna-induced signal levels with a spectrum analyzer. A preamplifier is usually necessary to improve the noise figure of the analyzer and obtain adequate sensitivity. The received levels can then be easily assessed for potential receiver degradation. This technique has been found to be very effective. Use of a spectrum analyzer is also helpful for RF compatibility assessment.

Other than for EIDs, margin assessment is practical in several areas. Margins can be assessed for antenna-connected receivers using the spectrum analyzer technique described above. Another area where margin evaluation is practical is potential degradation of subsystems due to electrical cable coupling from electromagnetic fields generated by on-board antenna-connected transmitters. Intra-system compatibility problems due to communication transmitters, particularly HF (2-30 MHz), are fairly common. The induced levels present in critical interface cables can be measured and compared to demonstrated hardness levels from laboratory testing in the same manner as described in the appendix under section 5.3 for inter-system EMC.

System-level testing should be a final demonstration that RF compatibility has been obtained. It should not be a starting point to identify areas requiring fixes. Previous analysis and bench testing should resolve compatibility questions beforehand.

Active signal cancellation techniques present a risky approach to EMC and should be rigorously tested before being implemented. This approach is most sensitive to signal phase error and may actually worsen an interference problem by injecting phase noise resulting from a changing multi-path situation (due to aircraft stores load, release, and so forth).

A5.2.1 Hull generated intermodulation interference (IMI). *For surface ship applications, the above requirement is considered to be met when the 19th product order and higher of IMI generated by High Frequency (HF) transmitters installed onboard ship are not detectable by antenna-connected receivers onboard ship. Compliance shall be verified by test, analysis, or a combination thereof, through measurement of received levels at system antennas and evaluation of the potential of these levels to degrade receivers.*

Requirement Rationale (A5.2.1): In general, control of IMI in systems is covered by the language of section 5.2 requiring intra-system electromagnetic compatibility. Because of difficulty on ships with limiting IMI produced by HF transmitters, only higher order intermodulation products must be controlled to permit effective use of the spectrum. Issues with lower order products are addressed through frequency management.

Requirement Guidance (A5.2.1): The large number of HF transmitters, output power of the transmitters, and construction materials and techniques used on ships make the presence of IMI a reality. Electromagnetic fields from HF transmissions induce current flow in the ships hull. The various currents from different transmitters mix in non-linearities within the hull (termed the "rusty bolt effect") to produce signals at sum and difference frequencies of the fundamental and harmonic frequencies of the incident signals ($F_3 = \pm n_1F_1 \pm n_2F_2 \pm ...$; n_1, n_2, ... are integers). The order of the IMI is the sum of the n terms. The mixing of a fundamental with a fourth harmonic produces a fifth order IMI.

Requirement Lessons Learned (A5.2.1): Experience has shown that controlling 19th order and higher IMI provides frequency management personnel with sufficient flexibility to effectively manage the spectrum.

Verification Rationale (A5.2.1): Test and associated analysis are the only effective means to verify IMI requirements.

Verification Guidance (A5.2.1): Guidance on evaluating IMI is available through the Ship EMC Improvement Program (SEMCIP) technical assistance network. Access to the data base can be obtained by contacting the Naval Surface Warfare Center, Code J54, Dahlgren, VA (Commercial phone 540-653-8021, military phone DSN 249-8021).

Verification Lessons Learned (A5.2.1): Testing, supported by analysis, has proven to be an effective tool in evaluating IMI.

A5.2.2 Shipboard internal electromagnetic environment (EME). *For ship applications, electric fields (peak V/m-rms) below deck from intentional onboard transmitters shall not exceed the following levels:*

a. Surface ships.

(1). Metallic: 10 V/m from 10 kHz to 18 GHz.

(2). Non-metallic: 10 V/m from 10 kHz to 2 MHz, 50 V/m from 2 MHz to 1 GHz, and 10 V/m from 1 GHz to 18 GHz.

b. Submarines. 5 V/m from 10 kHz to 1 GHz.

Compliance shall be verified by test of electric fields generated below deck with all antennas (above and below decks) radiating.

Requirement Rationale (A5.2.2): Specific controls must be imposed to limit internal electromagnetic fields for ship applications to ensure that the variety of electronic equipment used onboard ships will be able to function with limited risk of performance degradation. This approach is partially due to the methodology by which equipment is installed on ships. For system applications other than ships, it is generally the responsibility of the system integrator to ensure that fields internal to the system are controlled to levels consistent with immunity characteristics of installed equipment.

Requirement Guidance (A5.2.2): Many types of electronic equipment are used on ships which have not been designed to be used in higher level electric field environment. Most predominant in this group are NDI and commercial items. Therefore, the EME must be controlled to provide a level of assurance that the equipment will operate properly.

Requirement Lessons Learned (A5.2.2): Compatibility problems have been experienced with electronic equipment due to inadequate control of field coupling below deck.

Verification Rationale (A5.2.2): Testing is the only reliable method to determine the coupled EME to a reasonable level of certainty.

Verification Guidance (A5.2.2): Testing needs to be performed with frequency selective receivers (spectrum analyzer or EMI receiver) and appropriate antennas such as those used in Test Method RE102 of MIL-STD-462. Broadband omnidirectional E-field sensors, such as those used in Test Method RS103 of MIL-STD-462D, can be used to search for areas of higher fields. Since these devices are broadband, they will detect the resultant E-field from all sources present within the bandpass of the device. The dominant source of the reading may not be obvious. Also, since these devices do not use the peak detection function present in spectrum analyzers and EMI receivers, indicated levels may be well below actual peak levels, particularly for pulsed fields.

Verification Lessons Learned (A5.2.2): Measurements of the electric fields below deck is the only means of verifying compliance with the internal EME requirements.

A5.2.3 Powerline transients. *For Navy aircraft and Army aircraft applications, electrical transients of less than 50 microseconds in duration shall not exceed +50 percent or -150 percent of the nominal DC voltage or ±50 percent of the nominal AC line-to-neutral rms voltage. Compliance shall be verified by test.*

Requirement Rationale (A5.2.3): Electrical transient levels produced by utilization equipment on prime power busses need to be maintained below levels required to protect other equipment from potential upset or damage.

Requirement Guidance (A5.2.3): Power quality standards, such as MIL-STD-704 for aircraft and MIL-STD-1399 for ships, control the supply voltage for utilization equipment within specified limits. The voltage is maintained at a monitoring location termed the "point of regulation (POR)" with allocation for allowable voltage drops beyond the POR to the input of utilization equipment. MIL-STD-704 does not include provisions for the control of transients less than 50 microseconds in duration. Also, MIL-STD-461D no longer includes a transient emission requirement. Each equipment using power needs to control transients to levels that will not cause upset or damage to other power users. The requirement applies from the base of the transient on the normal power waveform to the peak of the transient.

Transient requirements for applications other than Navy aircraft and Army aircraft are either covered by other types of control requirements or are considered to be unnecessary. For example, ship requirements are addressed in MIL-STD-1399, Section 300. The Air Force does not impose the above requirement for aircraft because they have not experienced problems from direct conduction of faster transients between subsystems over the power buses and consider the imposed levels to be much too severe for Air Force applications. Power interfaces for avionics are typically quite robust and standard electromagnetic interference requirements impose significant immunity levels on avionics. The only direct conduction problems the Air Force has experienced on power busses is with longer-term, power surges.

Requirement Lessons Learned (A5.2.3): Powerline transients have caused unresettable upsets to the primary attitude reference system of a Navy fighter aircraft degrading weapons control functions and requiring mission abort. Aircraft problems have occurred on Air Force aircraft from coupling of transients from unsuppressed inductive devices onto signal interface lines. However, whenever transient levels on the power buses are investigated, the levels present are often insignificant. The general observation has been that voltage levels on the power waveform near an unsuppressed source may be high, but away from the source and on the power bus side of the switching device, the levels are much lower.

Verification Rationale (A5.2.3): Testing is the only viable approach to determine actual transient levels.

Verification Guidance (A5.2.3): Powerline transients should be measured on each power bus during power-on and power-off sequencing, mode switching of equipment, and power bus switching. These measurements should be performed at a the power distribution point. Due to the high frequency impedance effects and other losses on the power bus, measurements of any significant transients that are detected should be repeated as close to the other utilization equipment as possible to determine if the level at the equipment exceeds the limits.

Verification Lessons Learned (A5.2.3): Not applicable.

A5.2.4 Multipaction. *For space applications, equipment and subsystems shall be free of multipaction effects. Compliance shall be verified by test and analysis.*

Requirement Rationale (A5.2.4): It is essential that RF transmitting equipment and signals not be degraded by the action of multipaction. It is essential that multipaction not result in spurious signals that interfere with receivers.

Requirement Guidance (A5.2.4): Multipaction is an RF effect that happens strictly in a high vacuum. An RF field accelerates free electrons resulting in collisions with surfaces creating secondary electrons. These are accelerated resulting in more electrons leading to a major discharge and possible equipment damage. The guiding document for multipaction analysis is NASA TR 32-1500.

Requirement Lessons Learned (A5.2.4): Connectors, cables, and antennas have all been involved in multipaction incidents. Sometimes, the application of insulators on antennas or a vent in connectors is sufficient to limit multipaction or damage. In some cases, transmitted signal strength has been severely impacted. Multipaction in RF amplifier circuitry has been implicated in semiconductor and insulator degradation.

Verification Rationale (A5.2.4): Multipaction is a resonant phenomenon in the dimensions of frequency and power. An increase in power may well reduce the probability of multipaction. Analysis is absolutely necessary to determine how margin is shown. Since multipaction can show flaws in machining and dielectrics that no other test will indicate, testing also must be performed.

Verification Guidance (A5.2.4): All components experiencing RF levels in excess of 5V need to be tested for multipaction. The test equipment must provide adequate power and transient levels to show margin with respect to the operating state. VSWR measurements provide a crude method of detecting multipaction; however, it is better to detect free electrons or changes in harmonic emissions.

Verification Lessons Learned (A5.2.4): For multipaction to occur, seed electrons must be present. In space, these electrons are provided by radiation. Some tests at sea level have shown no multipaction on components, while severe multipaction occurred in orbit. It is vital that a source of radiation or electrons be provided to get an accurate test. Some claim that some metals like aluminum are self seeding. However, since the effect is strongly dependent on surface treatment, aluminum should not be depended upon to be self seeding.

A5.3 Inter-system EMC. *The system shall be electromagnetically compatible with its defined external EME such that its system operational performance requirements are met. For systems capable of shipboard operation, Table IA shall be used. For space and launch vehicle systems applications, Table IB shall be used. For ground systems, Table IC shall be used. For all other applications and if the procuring activity has not defined the EME, Table ID shall be used. Inter-system EMC covers compatibility with, but is not limited to, EME's from like platforms* *(such as aircraft in formation flying, ship with escort ships, and shelter-to-shelter in ground systems), friendly emitters and hostile emitters. Compliance shall be verified by system, subsystem, and equipment level tests; analysis; or a combination thereof.*

TABLE IA. External EME for systems capable of shipboard operations (including topside equipment and aircraft operating from ships) and ordnance

Frequency (Hz)	*Environment (V/m - rms)*	
	Peak	*Average*
10k-150M	*200*	*200*
150M-225M	*3,120*	*270*
225M-400M	*2,830*	*240*
400M-700M	*4,000*	*750*
700M-790M	*3,500*	*240*
790M-1000M	*3,500*	*610*
1G-2G	*5,670*	*1,000*
2G-2.7G	*21,270*	*850*
2.7G-3.6G	*27,460*	*1,230*
3.6G-4G	*21,270*	*850*
4G-5.4G	*15,000*	*610*
5.4G-5.9G	*15,000*	*1,230*
5.9G-6G	*15,000*	*610*
6G-7.9G	*12,650*	*670*
7.9G-8G	*12,650*	*810*
8G-14G	*21,270*	*1,270*
14G-18G	*21,270*	*614*
18G-40G	*5,000*	*750*

TABLE 1B. External EME for space and launch vehicle systems

Frequency (Hz)	*Environment (V/m - rms)*	
	Peak	*Average*
10k-100M	*20*	*20*
100M-1G	*100*	*100*
1G-10G	*200*	*200*

10G-40G	20	20

TABLE IC. External EME for ground systems

Frequency (Hz)	Environment (V/m - rms)	
	Peak	Average
10k-2M	25	25
2M-250M	50	50
250M-1G	1500	50
1G-10G	2500	50
10G-40G	1500	50

TABLE ID. Baseline external EME for all other applications

Frequency (Hz)	Environment (V/m - rms)	
	Peak	Average
10k-100k	50	50
100k-500k	60	60
500k-2M	70	70
2M-30M	200	200
30M-100M	30	30
100M-200M	150	33
200M-400M	70	70
400M-700M	4020	935
700M-1000M	1700	170
1G-2G	5000	990
2G-4G	6680	840
4G-6G	6850	310
6G-8G	3600	670
8G-12G	3500	1270
12G-18G	3500	360
18G-40G	2100	750

Requirement Rationale (A5.3): The threat presented by RF emitters around the world is becoming increasingly more hostile. Increased multi-national military operations, proliferation of both friendly and hostile weapons systems, and the expanded use of the spectrum worldwide have resulted in operational EMEs not previously encountered. It is therefore essential that these environments be defined and used to establish the inter-system EMC design requirements. Documents such as MIL-HDBK-235 list various land-based, ship-based, airborne, and battle-force emitters and associated environments. The electromagnetic fields from these emitters, which may illuminate systems, are very high and can degrade system performance if they are not properly addressed.

Operational problems resulting from the adverse effects of electromagnetic energy on ordnance systems are well documented. Problems include premature detonation, component failure, and unreliable built-in-test indications. These problems underscore the importance of designing ordnance systems that are compatible with their intended operational EME.

Joint service operations further increase the potential for safety and reliability problems if the system is exposed to operational EMEs different from those for which they were designed. For example, Army systems, if designed for compatibility with a single (land) EME, may be adversely affected by exposure to a Navy shipboard (joint operations) environment.

Table IA represents a maximum composite of Navy mainbeam, Army aviation land-based, and world-wide civilian aircraft certification EME levels. MIL-HDBK-235 was used to a large extent to develop this table.

Table IB was derived from an analysis of emitters near launch sites and potential illumination of space vehicles in orbit.

Table IC describes the minimum baseline EME for ground systems. The EME values for Table IC were derived from a ground scenario assuming certain separation distances from various classes of emitters. Dips in the EME were smoothed out so as not to imply a level of fidelity that does not really exist and to simplify testing.

The SAE AE-4R subcommittee and the European organization EUROCAE Working Group 33 developed the environments of Table ID as criteria for worldwide certification of civil aircraft. The increasing use of full authority flight and engine controls in aircraft demands consideration of these threats to ensure safety. These environments are quite severe and represent the absolute minimum that military aircraft must meet. This EME envelope has been verified by examining the databases for accuracy and by taking measurements of field strength through flight tests at selected sites. The civil airline community refers to this EME as the high intensity radiated fields (HIRF) environment. This environment is being imposed in this document as a reasonable default baseline for all military systems. Tailoring of the environment for particular systems is encouraged.

The FAA will be publishing an advisory circular and a HIRF users manual which will be helpful for designing to this environment. At publication time, these documents were not available.

Assumptions for the calculation of the Table ID EME environment are as follows. These details are provided as an example to demonstrate the many parameters that can be considered in developing a particular environment and to help in interpreting the environment.

a. All single transmitters and those in restricted air space are excluded.

b. Main beam illumination by transmitting antenna is assumed.

c. Maximum main beam gain of a transmitter antenna is used.

d. Modulation of a transmitted signal is not considered except that a duty cycle is used to calculate the average power for pulsed transmitters.

e. Constructive ground reflections of high frequency (HF) signals - that is, direct and reflected waves - are assumed to be in phase.

f. Non-cumulative field strength is calculated. Simultaneous illumination by more than one antenna is not considered.

g. Near-field corrections for the aperture and phased-array antennas are used.

h. Field strengths are calculated at minimum distances which are dependent on location of the transmitter and aircraft. The minimum distances are defined as follows.

(1) Airport environment

(a) 250 feet, slant range, for fixed transmitters within a 5-nautical-mile boundary around the runway with the exception of airport surveillance radar and air route surveillance radar. For these two radar types a 500-foot slant range is used.

(b) 500 feet, slant range, for fixed transmitters beyond a 5-nautical-mile boundary around the runway.

(c) 50 feet for mobile emitters, including those on other commercial aircraft, and 150 feet for airborne weather radar.

(2) Air-to-air environment.

(a) 500 feet for non-interceptor aircraft with all transmitters operational.

(b) 100 feet for interceptor aircraft with only non-hostile transmitters operational.

(c) Airborne warning and control aircraft are excluded.

(3) Ship-to-air environment.

A 2.4% gradient is used for the aircraft flight path, clearing the antenna by 300 feet. The ship is assumed to be 2.5 nautical miles from the end of the runway. Slant range is computed using maximum elevation angle. Where maximum elevation angle is not available, 45 degrees is used.

(4) Ground environments, including airport transmitters, while aircraft is in flight.

Aircraft are assumed to be at a minimum flight altitude of 500 feet and avoiding all obstructions, including transmitters, by 500 feet. Slant range is calculated for the maximum elevation angle for the transmitter antenna. If maximum elevation angle is not available, 90 degrees is assumed.

i. Field strength for each frequency band is the maximum for all transmitters within that band.

j. Peak and average.

(1) Peak field strength is based on the maximum authorized power of the transmitter and maximum antenna gain less system losses (estimated at 3 dB if not known).

(2) Average field strength is based on the average output power, which is the product of the maximum peak output power of the transmitter and maximum duty cycle. Duty cycle is the product of pulse width and pulse repetition frequency. $V_{Avg} = V_{Peak} \times (\text{duty cycle})^{1/2}$. This applies to pulsed systems only. The average power for non-pulsed signals is the same as the peak power (that is, no modulation present).

k. For transmitters in special use airspace, fields are calculated at the perimeter of the special use airspace.

Army aviation systems which are capable of shipboard operations are required to meet the shipboard operations EME of Table IA. Army aviation systems which are not capable of shipboard operations are required to meet the default EME of Table ID. For Army systems the actual operational electromagnetic environment is highly dependent upon operational requirements and should be defined by the procuring activity. The EME of these tables provide a starting point for an analysis to develop the actual external radiated field environment based on the system's operational requirements. The actual levels for most Army ground equipment will be somewhere in between the minimum baseline (Table IC) and the shipboard operations EME (Table IA). However, it is possible, due to special operational requirements or restrictions, for the actual environment to be higher or lower than these EME values. There is no substitute for well thought out criteria for a system based on its operational requirements.

An relevant aspect of environment definition is the development of both modulation and polarization requirements, in order to fully describe the peak and average fields over the entire frequency range. These requirements need to be based on the operational modulations of friendly, hostile, and civilian systems. For instance, amplitude modulation (AM) may cause substantial interference at low field levels, whereas continuous wave (CW) at significantly higher levels may not cause any interference. This type of difference can hold true for frequency modulation (FM) and pulse modulation (PM), as well as variations in polarization (vertical, horizontal, and circular).

Requirement Guidance (A5.3): The EME in which military systems and equipment must operate is created by a multitude of sources. The contribution of each emitter may be described in terms of its individual characteristics including: power level, modulation, frequency, bandwidth, antenna gain (mainbeam and sidelobe), antenna scanning, and so forth. These characteristics are important in determining the potential impact on system design. A high-powered emitter may illuminate the system for only a very short time due to its search pattern or may operate at a frequency where effects are minimized.

Antenna-connected receivers are not generally expected to operate without degradation for EME levels included in the table which are at or near the tuned frequency of the receiver. Channelized receivers should have sufficient selectivity to reject ambient RF energy that is within the receiver's tunable range but not at or near the desired channel of operation. Insufficient selectivity can result in saturation of the front end and undesirable processing of unwanted signals. In all cases, the receiver needs to be protected against burn-out.

The external EME must be determined for each system. When considering the external EMEs (flight deck, airborne, desert, battlefield and so forth), the following areas should be included in the evaluation.

a. Mission requirements. The particular emitters to which the system will be exposed depend upon its intended use. MIL-HDBK-235 provides information on the characteristics of many friendly and hostile transmitters.

b. Appropriate standoff distance from each emitter. MIL-HDBK-235 typically specifies fields 50 feet from the emitter. Fields at the distance that the system will pass by the transmitting antenna need to be determined.

c. The number of sites and where they are located. The probability of intercept for each emitter and the dwell time should be calculated.

d. If applicable, high power microwave and ultra-wideband emitters should be included.

e. Operational performance requirements (options of survivable only, degraded performance acceptable, or full performance required).

Requirement Lessons Learned (A5.3): Without specific design and verification requirements, problems caused by the external EME typically are not discovered until the system becomes operational. By the time interference is identified, the system can be well into the production phase of the program, and changes will be expensive. In the past, the EME generated by the system's onboard RF subsystems (electronic warfare, radars, communications, and navigation) produced the controlling environment for many systems. From a probability of exposure, these items still play a critical role. However, with external transmitter power levels increasing, the external transmitters can drive the overall system environment.

Issues with inter-system EMC have become more visible due to more joint operations among the military services and unforeseen uses of systems. For example, some aircraft and weapons that were not originally intended for shipboard use have been deployed onboard ships.

A complication with modern systems is the use of exotic types of structural materials. The classic system is made of aluminum, titanium, or steel structures. Modern technology and the need to develop higher performance systems are providing alternatives using composites such as carbon-epoxy and kevlar structure. Metals can provide good shielding against the EME and protection for electronic circuits. Electrically conductive composites typically provide system shielding comparable to metal at higher frequencies (approximately 100 MHz); however, at lower frequencies they do not perform as well. Some structure is made of non-conductive composites such as kevlar which provide no shielding, unless they are treated with appropriate finishes.

High-powered shipboard radars have caused interference to satellite terminals located on other ships, resulting in loss of lock on the satellite and complete disruption of communication. The interference disables the satellite terminal for up to 15 minutes, which is the time required to re-establish the satellite link. Standoff distances of up 20 nautical miles between ships are required to avoid the problem.

A weapon system suffered severe interference due to insufficient channel selectivity in the receiver's front end. Energy originating from electronic warfare systems and another nearby "sister" channelized weapon system (operating on a different channel but within the same passband) coupled into the victim receiver and was "processed," severely degrading target detection and tracking capability. Installation of an electronically tuned filter immediately after the antenna countered the off-channel interference problem by: 1) eliminating receiver front-end amplifier saturation and 2) reducing overload of the system processor with extraneous in-band signals.

An aircraft lost anti-skid braking capability upon landing due to RF fields from a ground radar changing the weight-on-wheels signal from a proximity switch. The signal indicated to the aircraft that it was airborne and disabled the anti-skid system.

An aircraft experienced uncommanded flight control movement when flying in the vicinity of a high power transmitter, resulting in the loss of the aircraft. If the mission profile of the aircraft and the anticipated operational EME had been more accurately considered, this catastrophe could have been averted.

Aircraft systems have experienced self-test failures and fluctuations in cockpit instruments, such as engine speed indicators and fuel flow indicators, caused by sweeping shipboard radars during flight-deck operations. These false indications and test failures have resulted in numerous unnecessary pre-flight aborts.

Aircraft on approach to carrier decks have experienced interference from shipboard radars. One such problem involved the triggering of false "Wheels Warning" lights, indicating that the landing gear is not down and locked. A wave-off or preflight abort could occur due to this EMI induced condition.

Aircrews have reported severe interference to communications with and among flight deck crew members. UHF emissions in the flight deck environment caused interference severe enough that crews could not hear each other for aircrew coordination. This problem poses a serious hazard to personnel with the potential for damage to, or loss of, the aircraft and aircrew during carrier flight deck operations.

Verification Rationale (A5.3): There are many different RF environments that a system will be exposed to during its lifespan. Many threats will be seen only infrequently. Normal operational testing of a system may expose it to only a limited number of threats. Dedicated testing and analysis are required to verify the system capability in all RF environments it may see.

Verification Guidance (A5.3): Inter-system EMC testing should be performed under laboratory conditions where the system under test and the simulated environment are controlled. Undesired system responses may require an electromagnetic vulnerability (EMV) analysis to determine the impact of the laboratory observed susceptibility on system operational performance. Only under unusual circumstances is system verification accomplished or system susceptibilities investigated by operational testing in the actual external EME. There is much less control on variable conditions, fewer system functions can generally be exercised, and expenses can be much greater. The results of the EMV analysis and operational testing guide the possible need for system modification, additional analysis or testing.

System-level testing of large platforms such as aircraft, tanks, and ships, are usually done in an open area test site. The system's inter-system environment is evaluated to determine: which frequencies are of interest from the possible emitters to be encountered by the system when deployed, optimum coupling frequencies to the system, potential system EMV frequencies, available simulators, and authorized test frequencies that can be radiated. Based on these considerations and other unique factors to the system or program, a finite list of test emitters is derived. For each test emitter the system is illuminated and evaluated for susceptibilities. The test emitters may be swept with fixed frequency steps or may dwell at selected frequencies. For air delivered ordnance, system-level testing should include: preflight, captive-carry, and free-flight configurations.

Ideally, the entire system should be illuminated uniformly at full threat for the most credible demonstration of hardness. However, at most frequencies, test equipment does not exist to accomplish this task. Established test techniques are based on the size of the system compared to the wavelength of test frequency. At frequencies where the system is small compared to the wavelength of the illumination frequency (normally below 30 MHz), it is necessary to illuminate the entire system uniformly or to radiate the system such that appropriate electromagnetic stresses are developed within the system. Where whole system illumination is not practical, various aspects of the system's major physical dimensions should be illuminated to couple the radiated field to the system structure. At frequencies (normally above 400 MHz) where the size of the system is large compared to the wavelength, localized (spot) illumination is adequate to evaluate potential responses by illuminating specific apertures, cables and subsystems. 30 to 400 MHz is a transition region from one concept to the other where either technique may be appropriate, dependent upon the system and the environment simulator.

Typically, for a new system, 4 to 6 positions are used for low frequency illumination and 12 to 36 positions are used for spot illumination at higher frequencies. The emitters are radiated sequentially in both vertical and horizontal polarization. Circular and cross polarization are usually not practical test radiators. For an existing system which is undergoing retesting after installation of a new subsystem, 2 positions are normally used for low frequencies and 2 to 4 positions for high frequencies.

For the situation where the external environment exceeds all available simulators or it is necessary to achieve whole system illumination, the method of bulk current testing may be used. The system can be illuminated from a distance to obtain near uniform illumination but at a low levels. The induced current on the cable bundles from the uniform external field is measured.

The induced current levels are then scaled to full current level based on the system's external environment. These extrapolated levels are compared to electromagnetic interference data on individual subsystems and equipment. If sufficient data in not available, cables can be driven at required levels on-board the system to evaluate the performance of the system. The cable drive technique has been applied up to 400 MHz.

The system during an inter-system EMC test is evaluated as a victim of interference from the environment. Modes of subsystems and equipment should include: built-in test (BIT), operational procedures common to the test emitter environment, (for example, carrier deck operations versus airborne weapons release for an aircraft), and backup modes.

Pre-flight inter-system testing of air delivered ordnance is conducted to ensure that the system can successfully perform those pre-flight operations required during service use. Operations such as aircraft initiated BIT and mission or target data up-loading and down-loading are performed while exposing the weapon to the test EME.

Captive-carry inter-system testing of air delivered ordnance is conducted to verify weapon survivability following exposure to the main beam operational EMEs. Since this test simulates the weapon passing through the radar's main beam during takeoff and landing of the host platform, the weapon should be operated as specified for those flight conditions - typically standby or off. The duration of weapon exposure to the EMEs from the main beam should be based on normal operational considerations. Verification of system survivability may, in many cases, be made utilizing the weapon BIT function. However, if this is not possible, verification utilizing an appropriate system test set is required.

Free-flight testing of ordnance is performed utilizing an inert, instrumented weapon which is suspended in a noise free environment (anechoic chamber) simulating free space. A mode-stirred chamber is frequently employed as a means of rapidly identifying EME induced susceptibilities. Since the RF entry points and aspect angles associated with specific susceptibilities cannot be determined in the mode-stirred chamber, use of the anechoic chamber is subsequently required. The free-flight test program consists of evaluating weapon performance during the launch, cruise, and terminal phases of flight, while exposed to friendly and hostile EMEs.

The formal verification test of a system for inter-system EMC usually comes late in system development. A system such as an aircraft often undergoes extensive development and integration tests first. The external environment that may be encountered during these tests must be reviewed and the status of the aircraft with regard to the environment must be evaluated for safety prior to flight. EMI testing of the subsystems can be used as a baseline of hardness. Limited inter-system testing of the systems for safety concerns due to specific emitters may be necessary or possible restriction on allowable operation (such as aircraft flight paths) may need to be imposed.

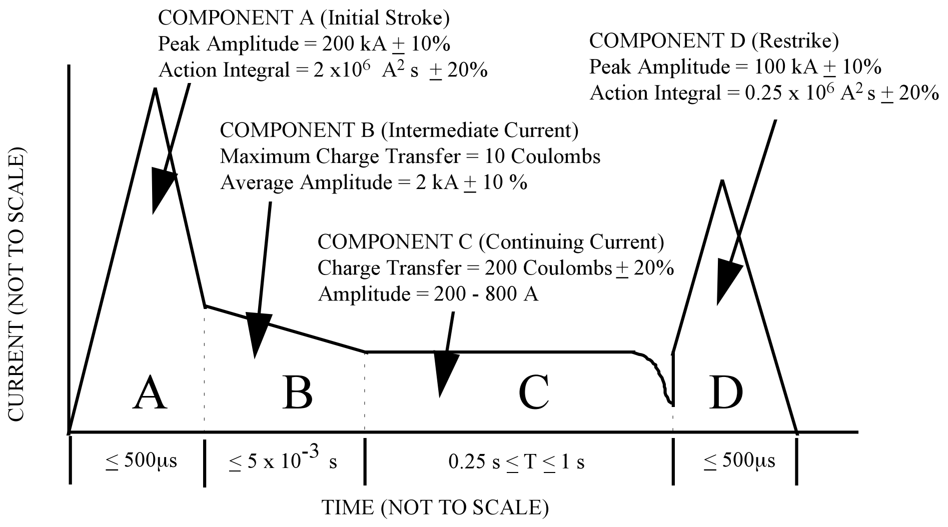
Verification Lessons Learned (A5.3): Failure to perform adequate inter-system EMC analysis or testing prior to system deployment has reduced the operation effectiveness and or availability of military platforms, systems, ordnance, and equipment. For instance, a review of the numerous reports in the Navy's Air Management Information Tracking System (AMITS) data base demonstrates that over half of reported incidents could have been prevented by completing an adequate verification program during the system's development. Access to the AMITS data base for personnel with a demonstrated need can be arranged through the Naval Air Warfare Center, Aircraft Division, Code AIR-4.1.7, Patuxent River, MD.

Field problems and test results have shown the main concern for system degradation is the frequency range below 5 GHz with the majority of major problems below 1 GHz. At system resonance, maximum coupling usually occurs with the environment. Resonance of the system structural features, apertures, and cables is usually between 1 MHz and 1 GHz. Test data indicates a linear increase in induced cable current levels with the frequency up to the quarter-wave resonance of a structure where induced levels flatten out and oscillate up and down at the quarter-wave level with increasing frequency. To detect these resonances during test, it is desirable to either sweep or use small increments of frequency.

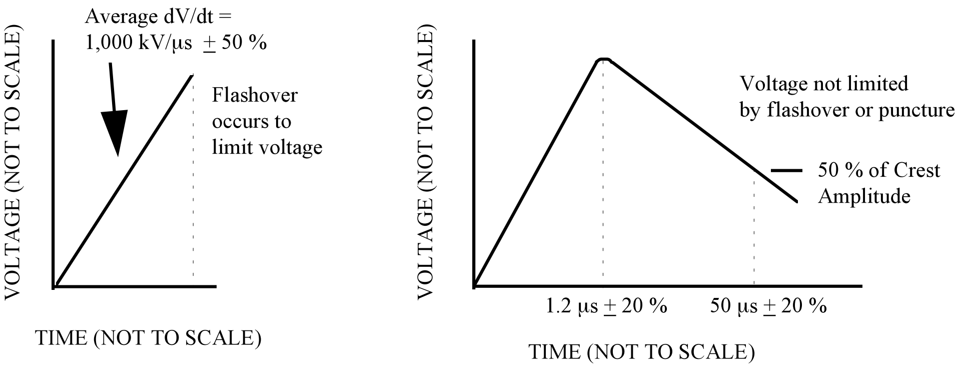
The predominance of problems at lower frequencies can be explained by considering coupling of a field to the area of a tuned aperture ($\lambda^2/4\pi$), which is proportional to the wavelength (λ) of the frequency squared. This aperture is an ideal area which is optimized for coupling maximum power from an incident field. This expression is multiplied in antenna theory by the gain of the antenna to determine the capture area of the antenna. The gain is simply assumed to be unity in this case. This concept can be viewed as either direct coupling through an aperture (opening) in system structure or coupling directly to subsystem circuitry treated as an antenna. As the wavelength becomes smaller with increasing frequency, the capture area becomes smaller and the received power is lower. In addition, as the frequency is increased, electrical cables are relatively poor transmission lines and coupling into subsystem becomes even less efficient, which leaves only direct penetration of enclosures as the main coupling path into the subsystem. As an example of the wavelength effect, the power coupled into a tuned aperture at 10 MHz for a given power density will be one million times greater that the power coupled into a tuned aperture at 10 GHz for the same power density: $(\lambda_1/\lambda_2)^2$ = (30 meters/0.03 meters)^2 = 1,000,000.

Typical test equipment used for the CW and high duty cycle tests are broadband distributed tube/transistor amplifiers and traveling wave tube (TWT) amplifiers together with long wire, vertical whip, double ridge horns, or dipole antennas. Typical test equipment used for pulsed tests are cavity tuned amplifiers, low duty cycle TWTs, magnetrons and klystrons with high gain horns.

A5.4 Lightning. *The system shall meet its operational performance requirements for both direct and indirect effects of lightning. Ordnance shall meet its operational performance requirements after experiencing a near strike in an exposed condition and a direct strike in a stored condition. Ordnance shall remain safe during and after experiencing a direct strike in an exposed condition. Figure 1 shall be used for the direct effects lightning environment. Figure 2 and Table IIA shall be used for the indirect effects lightning environment from a direct strike. Table IIB shall be used for the near lightning strike environment. Compliance shall be verified by system, subsystem, equipment, and component (such as structural coupons and radomes) level tests, analysis, or a combination thereof.*

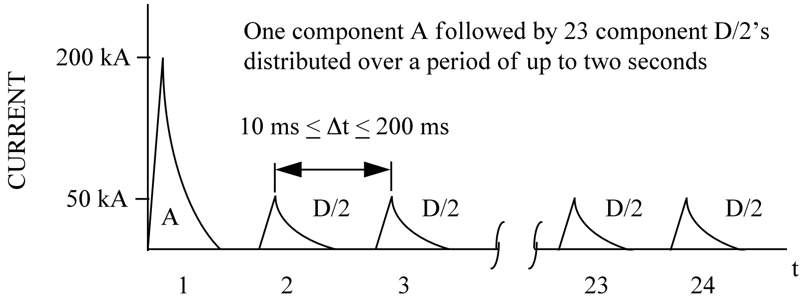


ELECTRICAL CURRENT WAVEFORMS

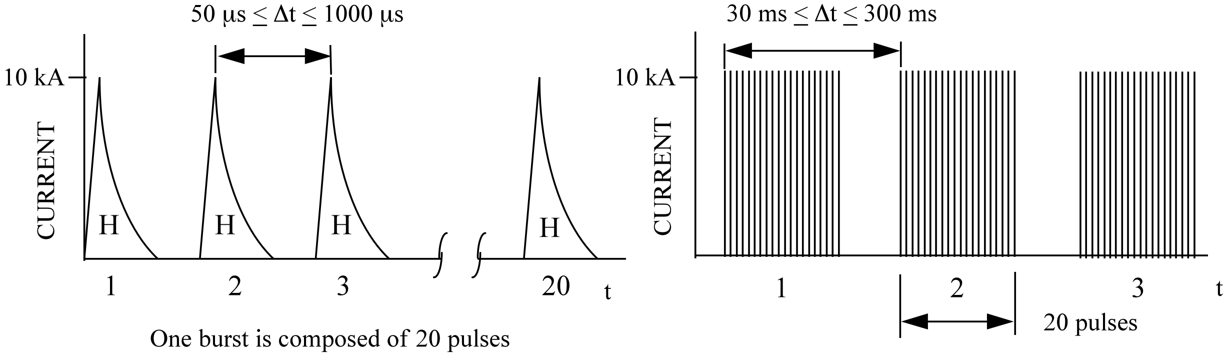


ELECTRICAL VOLTAGE WAVEFORMS

FIGURE 1. Lightning direct effects environment



MULTIPLE STROKE WAVEFORM



MULTIPLE BURST WAVEFORM

FIGURE 2. Lightning indirect effects environment

TABLE IIA. Lightning indirect effects waveform parameters

Current Component	*Description*	$i(t) = I_o (\varepsilon^{-\alpha t} - \varepsilon^{-\beta t})$ *t is time in seconds (s)*		
		I_o *(Amperes)*	α *(*s^{-1}*)*	β *(*s^{-1}*)*
A	*Severe stroke*	*218,810*	*11,354*	*647,265*
B	*Intermediate current*	*11,300*	*700*	*2,000*
C	*Continuing current*	*400 for 0.5 s*	*Not applicable*	*Not applicable*
D	*Restrike*	*109,405*	*22,708*	*1,294,530*
D/2	*Multiple stroke*	*54,703*	*22,708*	*1,294,530*
H	*Multiple burst*	*10,572*	*187,191*	*19,105,100*

TABLE IIB. Electromagnetic fields from near strike lightning (cloud-to-ground)

Magnetic field rate of change @ 10 meters	$2.2x10^9$ *A/m/s*
Electric field rate of change @ 10 meters	$6.8x10^{11}$ *V/m/s*

Requirement Rationale (A5.4): There is no doubt that lightning is hazardous for systems and that systems must include provisions for lightning protection. There is no known technology to prevent lightning strikes from occurring; however, lightning effects can be minimized with appropriate design techniques.

Lightning effects on systems can be divided into direct (physical) and indirect (electromagnetic) effects. The physical effects of lightning are the burning and eroding, blasting, and structural deformation caused by lightning, as well as the high pressure shock waves and magnetic forces produced by the associated high currents. The indirect effects are those resulting from the electromagnetic fields associated with lightning and the interaction of these electromagnetic fields with equipment in the system. Hazardous effects can be produced by lightning that does not directly contact system structure (nearby strikes). In some cases, both physical and electromagnetic effects may occur to the same component. An example would be a lightning strike to an antenna which physically damages the antenna and also sends damaging voltages into the transmitter or receiver connected to that antenna. DOT/FAA/CT-89/2 is an excellent source of lightning characteristics and design guidance.

An additional reason for requiring protection is potential effects on personnel. For example, serious electrical shock may be caused by currents and voltages conducted via mechanical control cables or wiring leading to the cockpit of an aircraft from control surfaces or other hardware struck by lightning. This effect can be quite hazardous in high performance aircraft, particularly under the thunderstorms conditions during which lightning strikes generally occur.

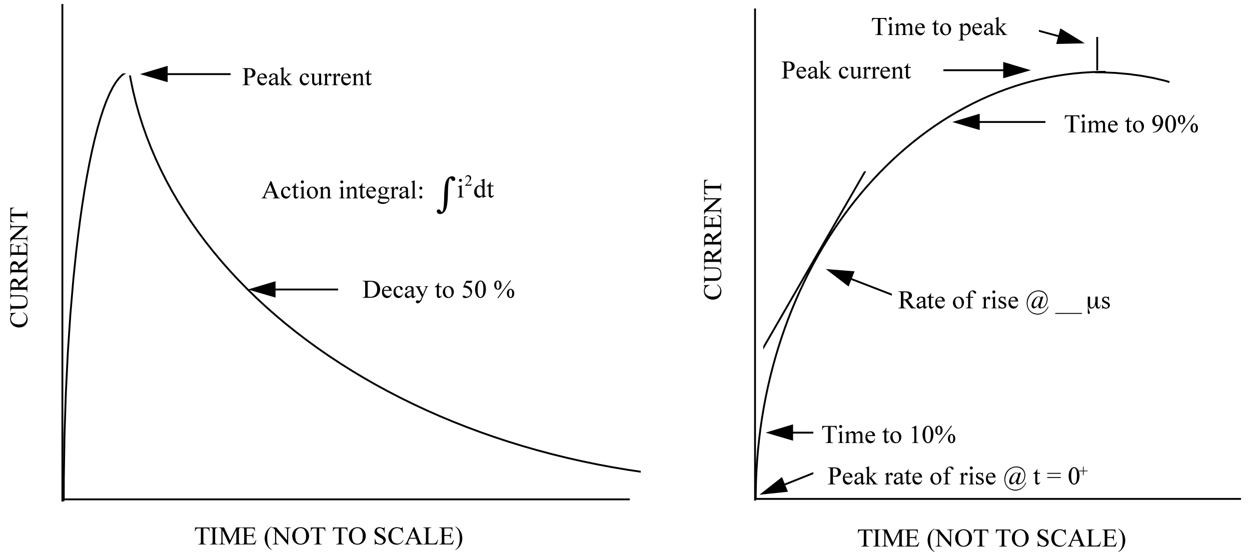
Shock can also be induced on flight crews under dielectric covers such as canopies by the intense thunderstorm electric fields. One of the most troublesome effects is flash blindness, which invariably occurs to a flight crew member looking out of the aircraft in the direction of the lightning and may persist for 30 seconds or more.

Requirement Guidance (A5.4): The direct effects environment is described in Figure 1. The indirect effects environment is described in Table IIA and Figure 2. In Table IIA, the indirect effects environment is defined by specifying parameters of a double exponential waveform (except for component C, which is a rectangular pulse) for the various electrical current components. Figure 2 represents a model of the properties of lightning events which include a series of strokes of significant current spaced over time (multiple stroke) and many individual strokes of lower current more closely spaced and grouped in bursts over time (multiple burst). This model is intended to be associated only with potential upset of electronics through indirect effects and is not intended to address physical damage issues. Figure A1 identifies important characteristics of the double exponential waveform and wavefront which are listed in Table AI for each of the indirect effects current components. The direct effects environment is derived from paragraph 3.0 of SAE Report "Lightning Test Waveforms and Techniques for Aerospace Vehicles and Hardware." The indirect effects environment is derived from Appendix III of SAE AE4L Committee Report AE4L-87-3.

TABLE AI. Lightning indirect effects waveform characteristics

Current compo-nent	Peak current (kA)	Action Integral (A^2s)	Decay to 50% (μs)	Time to 10% (μs)	Time to 90% (μs)	Time to Peak (μs)	Rate of rise (A/s)	Peak rate of rise t = 0+ (A/s)
A	200	2.0x10^{6}	69	0.15	3.0	6.4	1.0x10^{11} @ 0.5 μs	1.4x10^{11}
B	Produces average current of 2 kA over a 5 millisecond period							
C	Defined as rectangular waveform for analysis purposes of 400 A for 500 milliseconds							
D	100	0.25x10^{6}	34.5	0.08	1.5	3.18	1.0x10^{11} @ 0.25μs	1.4x10^{11}
D/2	50	6.25x10^{4}	34.5	0.08	1.5	3.18	0.5x10^{11} @ 0.25μs	0.7x10^{11}
H	10	N/A	4.0	0.0053	0.11	0.24	N/A	2.0x10^{11}

For space systems, the launch facility is expected to provide protection for the space and launch vehicles from a direct lightning strike. The space and launch vehicles themselves are not normally required to survive a direct strike. Indirect effects requirements for the space and launch vehicles apply for electromagnetic fields at a 100 meter or greater distance. The system should be capable of detecting any loss in operational performance before launch caused by a lightning strike.



WAVEFORM WAVEFRONT

FIGURE A1. Lightning indirect effects waveform parameters

Table IIB is a special case applied to ordnance for a nearby lightning strike. The indirect lightning requirements specified in Table IIA and Figure 2 are associated with the electrical properties of a direct attachment of lightning. Ordnance is not generally required to function after a direct attachment in the exposed condition. However, it must survive the electromagnetic coupling effects of a near strike as defined in Table IIB. Ordnance is required to survive a direct attachment to the container where the ordnance is stored.

As nearby lightning gets closer to an object, the effects approach those associated with the definitions for direct or indirect lightning. The peak field intensity of extremely close lightning can reach $3X10^6$ V/m. For any system hardened against the defined indirect effects lightning requirement, protection against nearby lightning is included. Many ground systems can accept some risk that the system operate only after a moderate lightning strike at a reasonable distance. For example, a requirement for equipment in a tactical shelter to survive a 90th percentile lightning strike at 50 m may represent a reasonable risk criteria for that shelter. This type of requirement would result in a high level of general lightning protection at a reduced design and test cost.

The direct and indirect effects environments, while describing the same threat, are defined differently to account for their use. The direct effects environment is oriented toward supporting available test methodology to assess the ability of hardware to protect against the threat. The indirect effects environment is more slanted toward supporting analysis. While these environments were developed for aircraft applications, they should represent a reasonable environment definition for other systems. Some recent measurements of natural lightning have indicated that spectral content of some strikes at higher frequencies may be greater than represented by the defined lightning models. For small systems, there could be some enhancement of coupling due to exciting of resonances

The SAE AE-4L lightning subcommittee has a cooperative effort underway with EUROCAE Working Group 31 to develop common documentation that can serve as non-Governmental standards for imposing lightning design and verification requirements. There will be a total of three documents: 1) lightning environment definition, 2) lightning test methods, and 3) lightning zoning of aircraft. When these documents become available, the international environment definition should replace the environment definition presently in this standard. The test methods document can be used for verification under section 5.4 and the aircraft zoning document can be used in the design process for lightning protection of aircraft.

While all airborne systems must be protected against the effects of a lightning strike, not all systems require the same level of protection. For example, an air-launched missile may only need to be protected to the extent necessary to prevent damage to the carrier aircraft.

Direct effects protection on all-metal aircraft has been generally limited to protection of the fuel system, antennas, and radomes. Most of the aircraft lost due to lightning strikes have been the result of fuel tank arcing and explosion. Other losses have been caused by indirect effects arcing in electrical wiring in fuel tanks. As aircraft are built with nonmetallic structures, protection of the fuel system becomes much more difficult and stricter attention to details is required. In general, some metal will have to be put back into nonmetallic structures to provide adequate lightning protection. FAA Advisory Circular AC 20-53 and its users manual provide requirements for protection of aircraft fuel systems.

In aircraft, lightning protection against indirect effects has become much more important due to the increased use of electrically and electronically controlled flight and engine systems. Also, the nonmetallic skins that are being used on aircraft to save weight provide less shielding to the electromagnetic fields associated with lightning strikes. FAA Advisory Circular AC 20-136 and its users manual provide indirect effects protection information.

If these documents are considered for use, the hazard terminology and various indirect effects transients requirements used by the civil air community need to be reviewed regarding their applicability to particular military procurements.

Specific protection measures for ground facilities are highly dependent on the types of physical structures and equipment involved. Devices such as lightning rods, arrestors, ground grids in the pavement, and moisture content of the soil all influence the protection provided. The guidance provided in MIL-E-4158, MIL-STD-1542, MIL- HDBK-454, and NFPA 780 addresses different design approaches to reduce lightning effects on equipment.

Requirement Lessons Learned (A5.4): A lightning strike to an aircraft is described as follows. As an aircraft flies through an electric field between two charge centers, it diverts and compresses adjacent equipotential lines. The highest electric fields will occur at the aircraft extremities where the lines are most greatly compressed. If the aircraft intercepts a naturally-occurring lightning flash, the on-coming step leader will intensify the electric field and induce streamers from the aircraft extremities. One of these streamers will meet the nearest branch of the advancing step leader forming a continuous spark from the cloud charge center to the aircraft. The aircraft becomes part of the path of the leader on its way to a reservoir of opposite polarity charge, elsewhere in the same cloud (intra-cloud strike), in another cloud (inter-cloud strike), or on the ground (cloud-to-ground strike). In many cases, the aircraft triggers the lightning event.

High peak currents occur after the stepped leader completes the path between charge centers and forms the return stroke. These peak currents are typically 30 - 40 kA; however, higher peak currents are encountered with peak currents in excess of 200 kA. The current in the return stroke rises rapidly with typical values of 10-20 kA/microsecond and rare values exceeding 100 kA/microsecond. Typically, the current decays to half its peak amplitude in 20-40 microseconds.

The lightning return stroke transports a few coulombs (C) of charge. Higher levels are transported in the following two phases of the flash. The first is an intermediate phase with currents of a few thousand amperes for a few milliseconds which transfers about 20 C. The second is a continuing current phase with currents on the order of 200-400 amps flowing for 0.1 to 1 second, which transfers about 200 C.

Typical lightning events include several high current strokes following the first return stroke. These occur at intervals of several milliseconds as different pockets in the cloud feed their charge into the lightning channel. The peak amplitude of the restrikes is about one half of the initial high current peak.

The effects of lightning can cause physical damage to personnel and equipment. In one of numerous documented lightning incidences, lightning appeared to enter a Navy aircraft nose, travel down the right side, and exit on top of the right vertical tail. The pilot suffered from flash blindness for 10-15 seconds. Upon regaining his vision, the pilot noticed all cockpit electrical power was gone. After another 15 seconds had elapsed, all cockpit electrical power returned on its own, with no cockpit indications of any equipment malfunction.

In another case, lightning attached to the nose pitot tube, inducing transients that damaged all 28 volt DC systems. The pilot, disoriented, broke out of a cloud bank at 2000 feet above the ground, at 600 knots and a 45 degree dive. Nearly all cockpit instruments were dysfunctional - compass, gyrohorizon, and so forth. A secondary effect occurred but was not uncovered for several months. The lightning current path that carried the direct effects lightning current did what it was supposed to do, but the path was not inspected on landing. Over 800 man-hours were expended to correct electrical (28 volt DC) problems but no effort went into inspecting for direct effects damage to ensure the lightning protection system was intact. The rigid coax from the front of the radome to the bulkhead had elongated and nearly torn away from its attachment point at the bulkhead due to magnetic forces involved. This damage reduced the effectiveness of the designed lightning protection. Another secondary effect was the magnetization of all ferrous material which caused severe compass errors. The entire aircraft had to be degaussed.

Verification Rationale (A5.4): Verification of lightning requirements is essential to demonstrate that the design protects the system from the lightning threat environment.

Verification Guidance (A5.4): There is no single approach to verifying the design. A well-structured test program supported by analysis is generally necessary. SAE AE4L Committee Report AE4L-87-3 contains information on the elements that are accepted as leading to proof of design. These same elements can be used for other electromagnetic effects areas such as electromagnetic pulse and the external EME.

During development of an system design, numerous development tests and analyses are normally conducted to sort out the optimum design. These tests and analyses can be considered part of the verification process, but they must be properly documented. Document details should include hardware definition, waveforms, instrumentation, and pass-fail criteria.

Flight testing of aircraft often occurs prior to verification of lightning protection design. Under this circumstance, the flight test program must include restrictions to prohibit flight within a specified distance from thunderstorms, usually 25 miles. Lightning flashes sometimes occur large distances from the thunderstorm clouds and can occur up to an hour after the storm appears to have left the area. Large pockets of charge can remain that can be discharged by an aircraft flying between oppositely charged pockets.

Verification Lessons Learned (A5.4): The naturally occurring lightning event is a complex phenomenon. The waveforms presented in this standard are the technical community's best effort at simulating the natural environment for design and verification purposes. Use of these waveforms does not necessarily guarantee that the design is adequate when natural lightning is encountered. One example is an aircraft nose radome that has lightning protection installed and verified by testing. When the aircraft is struck, natural lightning often punctures the radome. Subsequent testing has been unable to duplicate the failure. This result is most likely caused by our inability to duplicate the naturally occurring lightning event.

The use of non-metallic (composite) materials for parts such as fuel tanks and aircraft wings introduces the need for specific tests for sparking and arcing in these members. A test in the wet wing of an aircraft identified streamering and arcing from fastener ends. The tests resulted in a new process by the manufacturer to coat each fastener tip with an insulating cover.

A5.5 Electromagnetic pulse (EMP). *The system shall meet its operational performance requirements after being subjected to the EMP environment. If an EMP environment is not defined by the procuring activity, Figure 3 shall be used. This requirement is not applicable unless otherwise specified by the procuring activity. Compliance shall be verified by system, subsystem, and equipment level tests, analysis, or a combination thereof.*

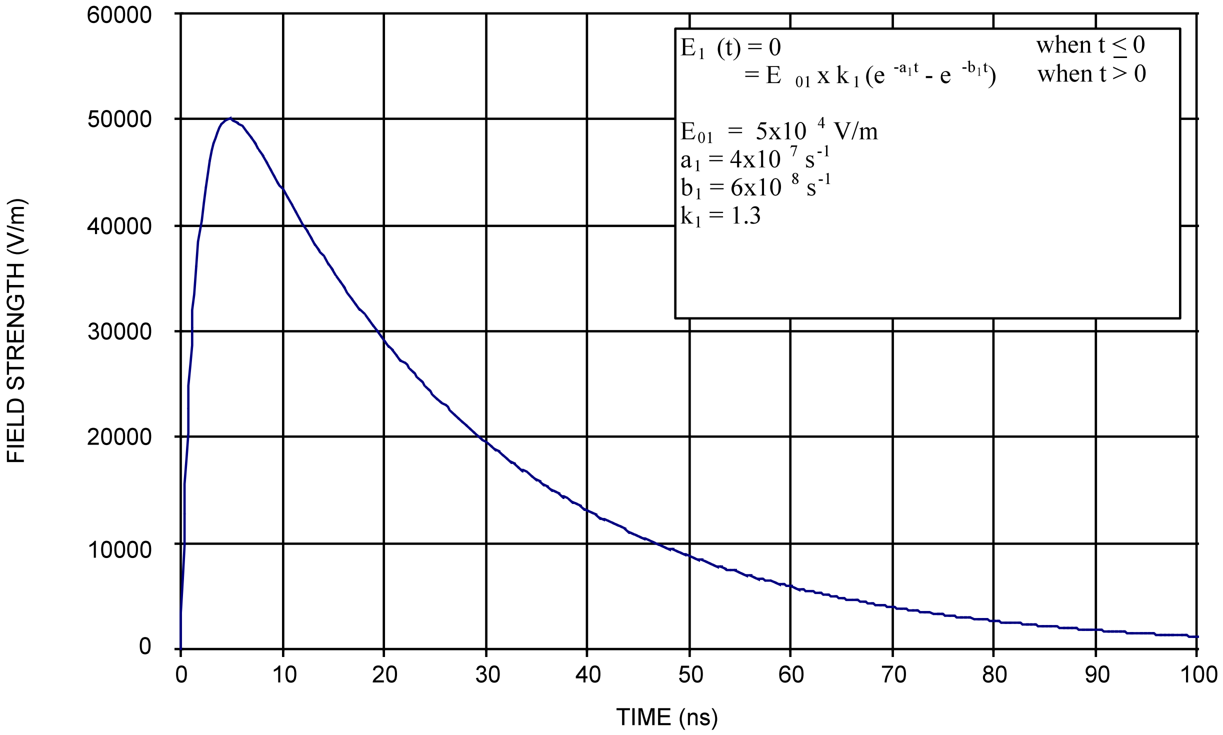


FIGURE 3. Default free-field EMP environment

Requirement Rationale (A5.5): High-altitude EMP (HEMP) is generated by a nuclear burst above the atmosphere which produces coverage over large areas and is relevant to many military systems. The entire continental US area can be exposed with a few bursts. Figure 3 provides an unclassified version of the free-field threat developed by the International Electrotechnical Commission (IEC). MIL-STD-2169, a classified document, provides detailed descriptions of the threat waveforms. In a nuclear war, it is probable that most military systems will be exposed to EMP.

Requirement Guidance (A5.5): EMP protection should be implemented for selected military systems. Many systems do not have a specific need expressed in their operational requirements for the EMP environment. In these instances, EMP requirements should not be imposed, since protection and verification can merely add unnecessary acquisition costs.

The electromagnetic (EM) fields near the surface of the ground that result from a high altitude nuclear burst are shown on Figure A2. The first part, often denoted E1 (prompt gamma signal), and specified in greater detail in Figure 3 is generated by the motion of Compton electrons made by prompt gammas from the burst. This mechanism dominates out to about a microsecond. Between 1 and 100 microseconds, the fields generated by previously scattered gammas are most important. This effect is denoted E2a (scattered gamma signal). Both the prompt and scattered gamma signals are usually represented as plane waves, with the approximate magnitudes shown in Figure A2. Between 1 and 10 milliseconds the dominant electric fields are generated by the gammas arising from the inelastic collision of high energy neutrons with air nuclei, and the effect is denoted E2b (neutron gamma signal). Mechanisms for the generation of HEMP in this time regime are strongly influenced by the presence of the ground, and the magnitude of the E2b vertical electric field is shown in Figure A2. Finally, at times on the order of a second to 100's of seconds, the motion in the geomagnetic field of ionized heated weapon debris and entrapped air induces electric fields in the ground. This effect is known as magnetohydrodynamic (MHD) EMP or E3. The portion of E3 which couples strongly to systems is the horizontal component of the electric field which is shown in Figure A2.

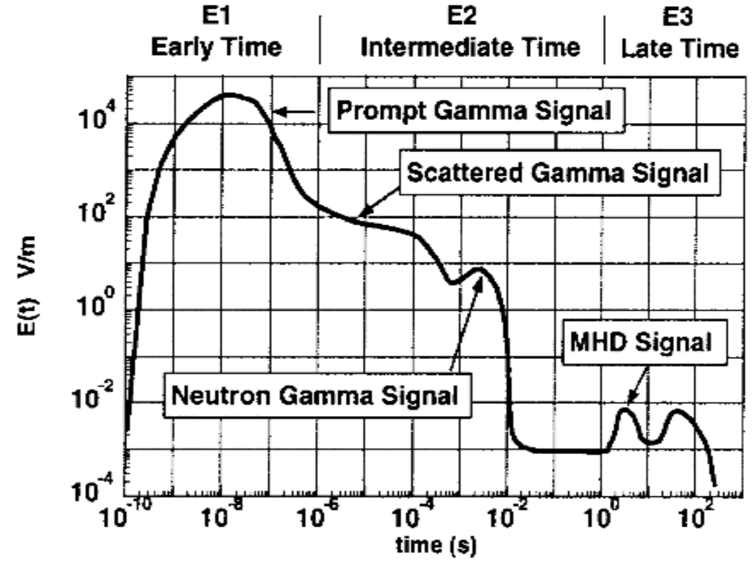


FIGURE A2. EMP environment (E1, E2, and E3)

The prompt gamma HEMP (E1) couples well to local antennas, equipment in buildings (through apertures), and to short and long conductive lines. E1 contains strong in-band signals for coupling to MF, HF, VHF and some UHF radios. The most common protection against the effects of E1 is accomplished using electromagnetic shielding, filters, and surge arresters. E1 can temporarily or permanently disrupt the operation of fixed, mobile, and transportable ground-based systems, aircraft, missiles, surface ships, and electronic equipment and components. Thus, E1 effects must be considered in protecting essentially all terrestrial military systems and equipment that must be capable of operating in a high-altitude nuclear EMP environment.

The scattered gamma HEMP (E2a) couples well to long conductive lines, vertical antenna towers, and aircraft with trailing wire antennas. Dominant frequencies are in the LF and VLF range. Protection against E2a is accomplished using EM filters and surge arresters.

The neutron inelastic gamma HEMP (E2b) couples well to long overhead and buried conductive lines and to extended VLF and LF antennas on submarines. Dominant frequencies overlap AC power and audio spectrums making filtering difficult.

Magnetohydrodynamic HEMP (E3) couples well to power and long communications lines including undersea cables. Low frequency content (sub Hertz) makes shielding and isolation difficult. Magnetic storm experience indicates significant probability of commercial power and land line disruption.

E1 is the most common portion of the EMP waveform which is imposed on systems and is therefore included in the main body of this standard as Figure 3. For system applications that need to address the E2 and E3 portions of the threat, MIL-STD-2169 should be consulted.

The requirement wording addresses meeting operational performance requirements “after” exposure to the EMP environment. This wording is a recognition that at the instant of the EMP event, the electrical transients present within the system may be causing some disruption of performance. Immediately after the event or within some specified time frame (driven by system operational performance requirements), the system must function properly.

MIL-STD-188-125 prescribes minimum performance requirements for low-risk protection of ground-based command, control, communications, computer, and intelligence (C^4I) facilities from mission-impacting damage and upset from the HEMP threat environments as defined in MIL-STD-2169. MIL-STD-188-125 also addresses minimum testing requirements for demonstrating that prescribed performance has been achieved and for verifying that the installed protection subsystem provides the operationally required hardness for the completed facility. The standard may also be used for other types of ground-based facilities that require hardening. MIL-HDBK-423 contains guidance on implementing the requirements of MIL-STD-188-125.

AFWL-TR-85-113 provides guidance on design considerations which address electromagnetic pulse concerns for aircraft.

While ionizing radiation is not within the scope of this document, some space vehicles have performance requirements during exposure to the ionizing radiation environments of a nuclear anti-satellite weapon. In those cases, the space vehicle needs to be designed to operate through and survive the effects. Specific requirements should be placed in relevant contracts.

Requirement Lessons Learned (A5.5): EMP poses a threat only to electrical and electronic equipment in systems. There are no structural damage mechanisms; however, EMP induced arcing of insulators on antenna systems can permanently damage the insulator, disabling the antenna. The EMP waveform results in a broadband transient excitation of the system. Transient currents are induced to flow at the natural resonance frequencies of the system. Currents may flow into internal portions of the system through direct conduction on electrical wiring or mechanical assemblies which penetrate external structure. The magnetic fields produced by the large external currents may couple voltages and currents into wiring internal to the system through any available apertures.

Ground-based military systems typically specify the HEMP environment even when other components of the nuclear environment are not specified. This threat is an electromagnetic field at ground level resulting from a high altitude burst. Hardening against ground-burst nuclear radiation environments is often not cost effective because a burst near enough to produce a radiation and electromagnetic threat is also close enough for the blast to disable the facility.

The most commonly observed effect from EMP is system upset. Burnout of electronics has occurred less frequently. However, as electronic chip sizes continue to decrease (sub-micron), the amount of energy required for burnout will reduce, and designers must insure that adequate interface protection is present. Upsets can range from mere nuisance effects, such as flickers on displays and clicks in headsets, to complete lockups of systems. Upsets which change the state of a system can be either temporary (resettable) or permanent. Some upset cases can be reset almost instantaneously at the time a switch is activated while others, such as reloading of software, may take minutes. With the introduction of safety critical functions controlled by electronics in systems, potential effects from upsets can be life-threatening.

Verification Rationale (A5.5): For systems with an EMP requirement, verification is necessary to demonstrate that implemented measures provide required protection. Both analysis and test are usually essential in verifying system performance.

Verification Guidance (A5.5): Analysis is the starting point for initial system design and for hardening allocations. Development tests are generally conducted to clarify analysis predictions as well as to determine the optimum designs. These analyses and tests are part of the overall design verification.

For many systems, the cost of EMP verification is a major driver. Therefore, the procuring activity should decide what level of verification is consistent with the risk that they are willing to take.

The following are elements of an iterative process for designing and verifying protection of a system's electrical and electronic equipment against the effects of EMP.

a. <u>EMP coupling analysis</u>. A coupling analysis is necessary to determine the EMP free-field coupling into the system. Existing coupling data on similar system designs should be used whenever possible. This analysis provides an estimate of the voltages and currents generated by the EMP at each interface of each mission-critical equipment and can be used to establish stress levels to be included in electromagnetic interference (EMI) requirements imposed on the equipment. Requirements CS115, CS116, and RS105 of MIL-STD-461D provide a basis for appropriate requirements for equipment.

b. <u>Identification of relevant subsystems</u>. Subsystems and equipment that may be affected by EMP, and whose proper operation is critical or essential to the operation of the system, must be identified. The equipment locations within the system need to be determined.

c. Equipment strength determination. The inherent hardness of equipment without specific EMI susceptibility requirements needs to be determined. These results together with existing EMI requirements on equipment establish a lower bound on the upset and damage thresholds for each mission critical equipment.

d. Specification compliance demonstration. Verification that the system meets EMP design requirements is accomplished by demonstrating that the actual transient levels appearing at the equipment interfaces do not exceed the hardness levels of the individual equipment or subsystem and that the required design margins have been met. Verification should be accomplished by a combination of test and analysis.

MIL-STD-188-125 contains verification test methods for demonstrating that C^4I ground-based facilities meet HEMP requirements. The test methods describe coupling of threat-relatable transients using pulse current injection to penetrating conductors at injection points outside of the facility's electromagnetic shielding barrier. Residual internal responses are measured, and the operation of mission critical subsystems is monitored for upset or damage. The standard also contains shielding effectiveness and CW illumination test procedures used to measure the performance of the facility shield.

Verification Lessons Learned (A5.5): Nuclear testing during the 1960's confirmed that the effects of nuclear EMP are significant well beyond the detonation site.

The choice of verification methods is somewhat dependent upon uncertainties associated with the available methods. Verification schemes that are oriented more toward analysis will usually introduce much larger uncertainties than test. Therefore, the required margins that must be demonstrated will be that much greater. Also, analysis is not capable of anticipating design flaws. For example, larger-than-anticipated current levels resulted during an aircraft system-level test due to metallic lines which had not been designed for proper electrical bonding entering a shielded volume. In another case, terminal protection devices did not operate due to the low impedance present in the circuit which they were designed to protect, and as a result, high current levels appeared in a shielded volume. Uncertainties in analysis can be reduced by selective testing of sections of the system.

Protection measures related to structural components should be evaluated for performance during assembly to verify that they meet requirements as installed in the system. After assembly, access to some components may not be practical. Passing a test in the laboratory does not necessarily mean that requirements will be satisfied in the actual assembly. Many times the final design contains materials, surfaces, or fasteners which are different from the laboratory model. Also, the complex geometry of a final system design may be so different from that which was modeled in the laboratory that the electromagnetic behavior is substantially altered.

There are a number of ways to obtain system-level excitation for purposes such as quality control or hardening evaluation. Low-level CW illumination of the system or of individual components is relatively easy and can often reveal an oversight in system assembly or a deficiency in the design of a hardening element. For aircraft, single point excitation (electrical connection of a signal source to a physical point on the external structure of the system) can be done (even in a hanger) and can similarly reveal any obvious problems in the airframe shielding.

Tests of structural design and hardening measures should be done as early in the assembly of the system as possible and should continue throughout the design process. If problems are uncovered during the initial assembly, the correction is usually straightforward. However, if the deficiencies are not found until the system is completed, the result can be a very expensive retrofit program. Analysis, laboratory testing, and system-level testing with low-level signals are important elements of compliance. However, a system-level test of a functioning system using a high-level EMP simulator is a high confidence method of demonstrating compliance.

A5.6 Subsystems and equipment electromagnetic interference (EMI). *Individual subsystems and equipment shall meet interference control requirements (such as the conducted emissions, radiated emissions, conducted susceptibility, and radiated susceptibility requirements of MIL-STD-461) so that the overall system complies with all applicable requirements of this standard. Compliance shall be verified by tests that are consistent with the individual requirement (such as testing to MIL-STD-462 to verify MIL-STD-461 requirements).*

Requirement Rationale (A5.6): EMI (emission and susceptibility) characteristics of individual equipments and subsystems must be controlled to obtain a high degree of assurance that these items will function in their intended installations without unintentional electromagnetic interactions with other equipments, subsystems, or external environments. The electromagnetic environment within a system is complex and extremely variable depending upon the various operating modes and frequencies of the on-board equipment. Also, system configurations are continuously changing as new or upgraded equipment is installed. Equipment developed on one platform may be used on other platforms. MIL-STD-461 and MIL-STD-462 provide a standardized set of interference control and test requirements which form a common basis for assessing the EMI characteristics of equipment.

Some of the primary factors driving the need for controls are the presence of sensitive antenna-connected receivers, which respond to interference generated within their tuning ranges, and the environments produced by on-board and external transmitters, lightning, and electromagnetic pulse.

Requirement Guidance (A5.6): The particular EMI requirements on individual items need to be specified based on system design concepts related to transfer functions between environments external to the vehicle and installation locations, isolation considerations with respect to other on-board equipment, and operational characteristics of other equipment. MIL-STD-461 and MIL-STD-462 are tri-service coordinated documents which standardize EMI design and test requirements. These requirements should be used as a baseline. Appropriate requirements for a particular application may also be obtained from commercial specifications, such as RTCA DO-160 or other industry standards. DO-160 contains a variety of limits which the equipment manufacturer can choose as a qualification level for his equipment. Care needs to be taken to ensure that an appropriate limit is used for a particular application. Unique requirements may also be specified as necessary. For example, additional requirements may be necessary for reasons such as lightning protection of systems using composite structure or spectrum compatibility. Section 5.6.1 provides additional guidance for the development of tailored EMI requirements for NDI and commercial items.

EMI requirements are separated into two areas, interference emissions from the subsystem and susceptibility (sometimes referred to as immunity) to external influences. Each of these areas have conducted and radiated controls. Most emission requirements are frequency domain related and data are taken with spectral analysis equipment, current probes for conducted measurements, and antennas for radiated measurements. Susceptibility requirements are usually defined in terms of conducted drive voltages and currents for transients and modulated sinusoids to evaluate power and signal interfaces and electromagnetic field levels for radiated signals. Susceptibility measurements are performed with a wide variety of signal sources, power amplifiers, injection devices, and antennas.

Electromagnetic coupling considerations for wiring and cable for space and launch vehicles can be found in MIL-W-83575.

Requirement Lessons Learned (A5.6): The limits specified in MIL-STD-461 are empirically derived levels to cover most configurations and environments; however, they may not be sufficient to guarantee system compatibility. Tailoring needs to be considered for the peculiarities of the intended installation. The limits have a proven record of success demonstrated by the relatively low incidence of problems at the system-level. There is usually reluctance to relax requirements since system configurations are constantly changing, and subsystems/equipments are often used in installations where they were not originally intended to be used. Measurements of a particular environment are usually not available and actual levels would be expected to vary substantially with changes of physical location on the system and with changes in configuration

Past experience has shown that equipment compliance with its EMI requirements assures a high degree of confidence of achieving system-level compatibility. Non-conformance to the EMI requirements often leads to system problems. The greater the noncompliance is with respect to the limits, the higher the probability is that a problem will develop. Since EMI requirements are a risk reduction initiative, adherence to the EMI requirements will afford the design team a high degree of confidence that the system and its associated subsystems will operate compatibly upon integration.

There is often confusion regarding perceived margins between emission and susceptibility requirements. The relationship between most emission control requirements and susceptibility levels is not a direct correspondence. For example, MIL-STD-461 requirement RS103 specifies electric fields which subsystems must tolerate. Requirement RE102 specifies allowable electric field emissions from subsystems. RE102 levels are orders of magnitude less than RS103 levels. Margins on the order of 110 dB could be inferred. The inference would be somewhat justified if the limits were strictly concerned with a one-to-one interaction such as wire-to-wire coupling of both RE102 and RS103 levels. This type of coupling is a minor concern for RE102. The driving reason for RE102 levels is coupling into sensitive RF receivers through antennas. The front-ends of receivers are typically many orders of magnitude more sensitive than wire-connected interfaces in systems. Similarly RS103 levels directly correspond to electromagnetic fields radiated from antenna-connected transmitters. These fields are typically orders of magnitude larger than fields produced by cable emissions. Consequently, the apparent excessive margins that can be erroneously inferred from MIL-STD-461 do not exist.

Verification Rationale (A5.6): Testing is required to demonstrate compliance with electromagnetic interference requirements. For most cases, analysis tools are not available which can produce credible results to any acceptable degree of accuracy.

Verification Guidance (A5.6): For programs using MIL-STD-461, MIL-STD-462 provides corresponding test methods for each MIL-STD-461 requirement (conducted and radiated requirements for emissions and susceptibility).

RTCA DO-160 is the commercial aircraft industry's equivalent of MIL-STD-461 and MIL-STD-462. Some of the larger commercial aircraft companies have their own in-house standards which the FAA accepts for certification. Some military aircraft (primarily cargo type) have a mixture of military and commercial subsystems. Subsystems that are newly designed or significantly modified should be qualified to MIL-STD-461 and MIL-STD-462. Unmodified off-the-shelf equipment usually does not require requalification providing acceptable electromagnetic interference data exists (MIL-STD-461 and MIL-STD-462, DO-160, or other approved test methods). Section 5.6.1 contains additional guidance on verification for NDI and commercial items. Some additional laboratory evaluation may be necessary to ensure their suitability for each particular application.

Verification Lessons Learned (A5.6): The “D” revisions of MIL-STD-461 and MIL-STD-462 emphasize testing techniques which are more directly related to measurable system-level parameters. For instance, bulk cable testing is being implemented for both damped sine transient waveforms and modulated continuous wave. The measured data from these tests can be directly compared to stresses introduced by system-level threats. This philosophy greatly enhances the value of the results and allows for acceptance limits which have credibility.

An argument has sometimes been presented in the past that successful completion of an intra-system compatibility test negates the need to complete electromagnetic interference tests or to comply with requirements. Electromagnetic interference tests must be completed prior to system-level testing to provide a baseline of performance and to identify any areas which may require special attention during the system-level testing. Also, system-level testing exercises only a limited number of conditions based on the particular operating modes and parameters of the equipment and electrical loading conditions. In addition, electromagnetic interference qualification of the subsystems provides protection for the system with configuration changes in the system over time. One particular concern is the addition of new antenna-connected receivers to the system, which can be easily degraded if adequate controls are not maintained.

A5.6.1 Non-developmental items (NDI) and commercial items.

NDI and commercial items shall meet EMI interface control requirements suitable for ensuring that system operational performance requirements are met. Compliance shall be verified by test, analysis, or a combination thereof.

Requirement Rationale (A5.6.1): NDI and commercial items may be installed in systems for any number of reasons - economic, availability, and so forth. When installed in the system, the NDI and commercial items need to comply with the system level E^3 requirements of this standard. Therefore, NDI and commercial items must have suitable EMI characteristics such that they are not susceptible to electromagnetic stresses present in their installation and that they do not produce interference which degrades other equipment. Most equipment built these days is designed and tested to some form of EMI requirement and the data may be available. Other equipment may require testing.

Requirement Guidance (A5.6.1): The use of NDI or commercial items presents a dilemma between the need for imposing EMI controls and the desire to take advantage of existing designs, which may have unknown or undesirable EMI characteristics. Blindly using NDI or commercial items carries a risk of incompatibilities onboard the system. To mitigate the risk, a suitability assessment is required to evaluate the installation environment and the equipment's EMI characteristics through a review of existing data, review of equipment design, or limited testing.

Existing EMI test data should be reviewed to determine if the equipment is suitable for the particular application intended. If a piece of NDI or commercial item is being considered for use as mission equipment on an aircraft, then the equipment should meet the same EMI requirements as imposed on other equipment on the aircraft. However, if the NDI or commercial item is being considered for use in an electromagnetically hardened ground shelter, then imposition of EMI requirements may not be necessary. Each potential use of NDI or commercial items needs to be reviewed for the actual usage intended, and a determination needs to be made of appropriate requirements for that application.

The following guidelines should be considered in selecting and utilizing NDI or commercial items in the system:

a. The equipment EMI characteristics may be considered adequate if the specific requirements for installed equipment on a particular system developed from transfer functions are less stringent than those to which the equipment was designed and applicable EMI test data is available to verify compliance. Compliance with the equipment-level EMI requirements does not relieve the developing activity of the responsibility of providing system compatibility.

b. Where compliance with applicable equipment-level EMI requirements cannot be substantiated, laboratory EMI testing should be performed to provide the data necessary to demonstrate compliance with the requirements.

c. If after evaluation of the equipment level EMI data, it is determined that the equipment would probably not meet the system compatibility requirements, then it is the responsibility of the developing activity to implement design modifications to meet the required EMI levels or to select other equipment with adequate characteristics.

Requirement Lessons Learned (A5.6.1): There have been both good and bad EMI results with the use of NDI and commercial items in the past. The military has taken some commercial aircraft avionics equipment and installed them on land-based military aircraft with good results. This is due to the fact that these equipments were tested and qualified to a commercial aircraft EMI specification such as RTCA DO-160. In some cases, the commercial avionics required EMI modifications to make them compatible with a more severe electromagnetic environment on the military aircraft. Forward-looking infrared sensors originally developed for commercial police use were not compatible in the Army helicopter EME and significant restrictions on their use needed to be imposed. A night vision system developed by the Army was procured by the

Navy as NDI. Significant EMC problems were experienced aboard ship due to the higher shipboard EME.

Several instances have been noted in ground-based applications where EMI emissions from commercial digital processing equipment have interfered with the operation of sensitive radio receivers. Of particular concern are radiated emissions from processor clock signals causing interference with communications equipment that operates from 30 to 88 MHz. Most commercial equipment is qualified by testing at a distance of three meters. The problems have been largely caused by use of the commercial items at distances of one meter or closer where the fields will be higher.

An example of NDI and commercial item problems at the system-level, that most travelers have observed, is restrictions on the use of portable electronic devices on commercial aircraft during take-off and landings. These restrictions are in place because of several problems noted with coupling of interference from the portable electronics to antenna-connected receivers used for navigation and communications .

The military has successfully used NDI and commercial items in many other situations. Electronics maintenance shops generally use test equipment built to commercial EMI specifications or industry standards without requiring modifications. Ground system applications of data-processing equipment, displays, and office equipment used with other commercial items and NDI has been successful, where care has been taken with integration. The primary emphasis needs to be whether the equipment is suitable for that particular application.

When a delivered item is composed of a number of individual pieces of equipment, it is sometimes more cost-effective to qualify an integrated assembly rather than the individual pieces of equipment. Also, the performance of the integrated assembly, as installed in the system, is the more important issue since the EMI characteristics of the individual items may be modified by integration.

Verification Rationale (A5.6.1): When EMI requirements are needed on NDI or commercial items, then EMI testing data are required to demonstrate compliance with those requirements. The equipment cannot be susceptible to EMI that would degrade it or render it ineffective. Likewise, the equipment cannot be a source of EMI that impacts the operation of other equipment within the system. NDI and commercial items may have been previously qualified to a wide variety of types of EMI requirements. Analysis of the applicability of the particular type of EMI qualification in relation to a particular system installation will be necessary.

Verification Guidance (A5.6.1): Verification is required for the particular requirements imposed for the system installation. If the NDI or commercial items selected are currently in military use, then in all probability EMI test data exist which can be evaluated for suitability.

Verification requires an understanding of the installation environment both from the aspect of electromagnetic stresses present and potential susceptibility of equipment and from knowing the EMI characteristics of NDI and commercial items well enough to reach conclusions on system compatibility.

Verification Lessons Learned (A5.6.1): Most commercial equipment is qualified by testing at a distance of three meters. MIL-STD-462 uses one meter. When considering the use of NDI or commercial items, the location of the equipment with respect to system antennas needs to be considered in assessing the suitability of the equipment. The data from the three meter distance may be appropriate. It is difficult to translate the resulting commercial data to one meter. This situation is due to variable field impedances associated with near-field emissions and variations in indeterminate near-field emission patterns.

NDI and commercial avionics qualified to a commercial specifications, such as RTCA DO-160, are generally acceptable for military use on land-based aircraft, since the commercial and military EMI standards for airborne avionics are very similar in the tests required and the limits imposed. Over time, more general use electrical and electronic type devices are being required to meet some form of EMI requirement. In some cases, those would also be acceptable for military use, and, in other cases, more testing or qualification to a tighter limit may be required.

Some testing to characterize important qualities of the NDI and commercial items will often be necessary. For example, if coupling to particular receivers is the concern, an RE102 test from MIL-STD-462D limited to particular frequency bands may be all that is necessary.

Another example is a commercial global positioning system (GPS) receiver interfering with a military GPS receiver. The out-of-band antenna emissions from the commercial receiver were picked up by the antenna of the military receiver and processed at the in-band frequency. A limited CE106 test may have identified the emission.

A5.6.2 EM spectrum compatibility. *Subsystems and equipment shall comply with the DoD, national, and international regulations for the use of the electromagnetic spectrum (such as NTIA "Manual of Regulations and Procedures for Radio Frequency Management" and DoDD 4650.1). Compliance shall be verified by test, analysis, or a combination thereof, as appropriate for the equipment development stage.*

Requirement Rationale (A5.6.2): The availability of adequate spectrum to support military electronic systems and equipment is critical to maximizing mission effectiveness. Spectrum planning and frequency management must be given appropriate and timely consideration during the development, procurement, and deployment of military assets that utilize the electromagnetic spectrum.

To ensure maximum compatibility among the various worldwide users of the electromagnetic spectrum, it is essential that antenna-connected equipment comply with spectrum usage and management requirements. The DoD's use of the spectrum is constantly being challenged by the commercial sector. It is expected that the military's control of the spectrum will diminish in favor of commercial use. As more and more spectrum is taken away, the available spectrum must be managed as efficiently as possible to ensure the success of all military operations.

Requirement Guidance (A5.6.2): International spectrum management policy originates from the International Telecommunications Union (ITU) which establishes world-wide radio regulations. The U.S. national hierarchy for spectrum management was established by the Communication Act of 1934. Under the Communications Act, the Federal Communications

Commission (FCC) oversees the U.S. civilian use of the spectrum, and the Department of Commerce, National Telecommunications and Information Administration (NTIA), oversees the federal government's use of the spectrum. The Director, NTIA, executes these duties through the Interdepartment Radio Advisory Committee (IRAC), which consists of 20 representatives from government departments and agencies, including a representative from each military service. The Assistant Secretary of Defense for Communications, Command, Control and Intelligence (C^3I) oversees spectrum management within the DoD.

Spectrum certification is a legal requirement derived from Office of Management and Budget (OMB) Circular No. A-11 and DoDD 4650.1. Paragraph 13-2 (o) of OMB Circular No. A-11 states: "Estimates for the development or procurement of major communications-electronics systems (including all systems employing space satellite techniques) will be submitted only after certification by the National Telecommunications and Information Administration, Department of Commerce, that the radio frequency required for such systems is available."

Spectrum certification denotes the supportability of an electronic system or equipment for operation in a designated frequency band. The DoD spectrum certification process requires that a DD Form 1494, "Application for Frequency Allocation," be submitted through appropriate service frequency managers for approval. Instructions are delineated by each service for compliance with spectrum certification regulations. An approved frequency allocation authorizes the development or procurement of electronic systems in a defined frequency band or specified frequencies. Without an approved frequency allocation the program manager does not have the authority to procure electronic equipment, including commercial items.

The program manager is responsible for obtaining an approved frequency allocation for his system. Contractors may support the program manager in acquiring data for describing the item, but the program manager has the responsibility for submitting the frequency allocation application. The various stages applicable for obtaining spectrum certification are defined below:

a. Stage 1 (Conceptual) approval is required for the Pre-Concept phase. A frequency allocation for Stage 1 must be requested (DD Form 1494) and approved prior to the releasing of funds for studies or assembling "proof-of-concept" test beds. The system purpose, planned frequency range and power, and any other planned or estimated details must be provided concerning the item that are available.

b. Stage 2 (Experimental) approval is required prior to contracting for the Concept Exploration and Definition phase. An approved frequency allocation for Stage 2 is required prior to the release of funds for building a radiating test model or obtaining an approved frequency assignment for experimental usage. Estimated and calculated data can be used for nearly all of the blocks on DD Form 1494 when requesting a frequency allocation for Stage 2.

c. Stage 3 (Developmental) approval is required prior to contracting for the Engineering and Manufacturing Development phase. An approved frequency allocation for Stage 3 is required prior to the release of funds for developmental and operational testing. Frequency assignments must likewise be obtained prior to operation of radiating equipment. Calculated data is acceptable during Stage 3.

d. Stage 4 (Operational) approval is required prior to contracting for the Production and Deployment phase. Prior to contracting for production units, an approved frequency allocation for Stage 4 is mandatory. Measured data is mandatory for Stage 4. Calculated data is generally unacceptable. Commercial items normally require Stage 4 approval; however, if extensive modifications to the commercial item is planned, then Stage 3 may be appropriate.

Prior to operating electronic systems and equipment that intentionally transmit or receive electromagnetic radiation, a frequency assignment which authorizes the use of specified frequencies is required.

Design requirements for radar equipment and subsystems which are related to spectrum compatibility are provided in MIL-STD-469. The minimum design requirements in MIL-STD-469 satisfy Section 5.3, Radar Spectrum Engineering Criteria, in the NTIA manual. MIL-STD-469 also provides design requirements for radars that are more stringent than the NTIA standards for systems that operate in critical EMEs.

Analysis techniques addressing spectrum compatibility are found in Air Force document R-3046-AF.

Requirement Lessons Learned (A5.6.2): Currently there are numerous incidences of co-site, intra-ship, and inter-ship interference, as well as interference with the civilian community. For example, the Honolulu Airport air traffic control radars have been degraded by shipboard radars stationed adjacent to Pearl Harbor.

A program manager developed a system without requesting spectrum certification. After development, it was discovered that the system had the potential to interfere with other critical systems. Costly EMC testing and operational restrictions resulted, impacting the ability to meet mission requirements. Both items could have been avoided if spectrum management directives had been followed.

A base communications officer funded the purchase of commercially approved equipment. The user was unable to get a frequency assignment because the equipment functioned in a frequency range authorized for only non-government operation. A second system had to be purchased to satisfy mission requirements.

A tactical user bought commercial items as part of a deployable communications package. Because spectrum certification was not acquired and resulting host nation coordination for the use of that equipment was not accomplished, the user found that they were unable to use the equipment in the host European and Asian countries. This problem would have been identified prior to purchase had the proper coordination taken place. The user was unable to meet communication needs and had to buy additional equipment to satisfy requirements.

Verification Rationale (A5.6.2): Spectrum certification practices must be properly followed including verification of the characteristics of systems, subsystems, and equipment to ensure that they are in compliance with spectrum usage requirements.

Verification Guidance (A5.6.2): Frequency allocation requests must include technical information on the operating characteristics of the equipment to assist authorities in determining the disposition of the request. When requesting a frequency assignment, the developing activity should verify that the DoD Frequency Coordinator has approved the request as required. The data required is detailed on the DD Form 1494. The stage of the request determines the level of testing or analysis required. MIL-STD-462, MIL-STD-449, and MIL-STD-469 provide guidance for measuring the electromagnetic signal characteristics.

Verification Lessons Learned (A5.6.2): Numerous developed systems have been delayed in being allowed to operate because of the lack of an approved allocation.

A5.6.3. Shipboard DC magnetic field environment. *Subsystems and equipment used aboard ships shall not be degraded when exposed to its operational DC magnetic environment (such as MIL-STD-1399, Section 070). Compliance shall be verified by test.*

Requirement Rationale (A5.6.3): High level DC magnetic fields are intentionally generated onboard ships for degaussing and equipment must be able to operate in the presence of these fields.

Requirement Guidance (A.5.6.3): MIL-STD-1399, Section 070, provides requirements and guidance for protection of equipment against DC magnetic fields. Shipboard measurements have shown DC magnetic fields varying between 40 and 640 A/m dependent on location and time during normal operations and 1600 A/m during deperming. They tend to be the highest below the flight and weather decks. A typical requirement imposed on equipment is to operate in 400 A/m and to survive 1600 A/m. Another important parameter is the rate of change that the magnetic field can vary, which is 1600 A/m per second. Ship surveys to determine magnetic fields are useful in locating areas where the fields are less than 400 A/m or tailoring the requirement for a particular installation location. There will be cases where performance in 1600 A/m is required or where localized shielding will need to be used in the installation.

Requirement Lessons Learned (A5.6.3): Items most commonly influenced by DC magnetic fields and its variations are cathode ray tube monitors. The earth's magnetic field varies in magnitude between 24 and 56 A/m. These fields are as large as the ship generated field in some cases. Mobile platforms may experience changes of two times the local earth field simply through motion and the changing orientation of the platform. Unmodified commercial monitors can experience picture distortion when local fields change as little as 16 A/m.

Verification Rationale (A5.6.3): Testing is the only effective means to verify compliance.

Verification Guidance (A5.6.3): MIL-STD-1399, Section 070, provides guidance on test methodology. Testing normally needs to be performed in all three axes of orientation, although this is not always possible because of equipment size.

Verification Lessons Learned (A5.6.3): Simulating the rate of change in the field is sometimes more important than the absolute field magnitude.

A5.7 Electrostatic charge control. *The system shall control and dissipate the build-up of electrostatic charges caused by precipitation static (p-static) effects, fluid flow, air flow, space and launch vehicle charging, and other charge generating mechanisms to avoid fuel ignition and ordnance hazards, to protect personnel from shock hazards, and to prevent performance degradation or damage to electronics. Compliance shall be verified by test, analysis, inspections, or a combination thereof.*

Requirement Rationale (A5.7): Voltages associated with static charging and energy released during discharges are potentially hazardous to personnel, fuel vapors, ordnance, and electronics.

Dust, rain, snow, and ice can cause an electrostatic charge buildup on the system structure due to charge separation and the phenomenon called precipitation static charging.

Sloshing fuel in tanks and fuel flowing in lines can both create a charge buildup resulting in a possible fuel hazard due to sparking. Any other fluid or gas flowing in the system (such as cooling fluid or air) can likewise deposit a charge with potentially hazardous consequences.

During maintenance, contact of personnel with the structure can create an electrostatic charge buildup on both the personnel and structure (particularly on non-conductive surfaces). This buildup can constitute a safety hazard to personnel or fuel or may damage electronics. Potentially susceptible electronic parts are microcircuits, discrete semiconductors, thick and thin film resistors, integrated circuits, hybrid devices, and piezoelectric crystals, dependent upon the magnitude and shape of the electrostatic discharge (ESD) pulse.

Ordnance is potentially susceptible to inadvertent ignition from electrostatic discharge. The primary concern is discharge through the bridgewire of the EID used to initiate the explosive.

Space and launch vehicles experience charge separation effects in space from sunlight shining on the surface of the vehicles.

Requirement Guidance (A5.7): Any component of the system structure can accumulate an electrostatic charge and adequate means must be provided to dissipate the charge at low levels to prevent any significant voltage from developing. Electrically conductive and non-conductive materials behave differently. Charge deposits on conductive materials will migrate in the material such that all portions are at the same electrical potential. Charges deposited on purely non-conductive material cannot move and large voltage differences can exist over small distances.

Control of static charging is accomplished by ensuring that all structural surfaces are at least mildly conductive, that all components are electrically bonded, and that an electrical path to earth is provided. In general, conductive coatings need to be applied to all internal and external sections of the system structure which are electrically non-conductive. For most applications, 10^6 to 10^9 ohms per square is sufficient to dissipate the charge buildup. The shock hazard to personnel begins at about 3000 volts; therefore, the charge on system components should not be allowed to exceed 2500 volts.

Systems must incorporate features to minimize the possibility of sparks within the fuel system. The system design must consider the electrical conductivity of the fuels to be used and control the conductivity, if necessary. Fuel vapors can be ignited with about 0.25 millijoules of energy. As with structural features of the system, any component of the fuel system can accumulate an electrostatic charge and adequate means must be provided to dissipate the charge. Electrical bonding, grounding, and conductive coating measures need to be implemented. Fuel lines routed through fuel tanks require special attention. Additional information on static electricity and fuels is provided in AFAPL-TR-78-56 and AFAPL-TR-78-89.

The fuel system must also prevent sparking within the fuel tanks during refueling operations. Some useful requirements are: 1) bonding and grounding of fuel components, 2) limiting line velocities to no more than 30 feet per second, 3) limiting tank entry velocity to no more than 10 feet per second, and 4) refueling the tank from the bottom. Guidance for the control of static electricity during refueling of aircraft is presented in TO 00-25-172.

NASA document TP2361 provides design guidelines for space and launch vehicle charging issues. Subsystems and equipment installed aboard space systems should be able to meet operational performance requirements during and after being subjected to a 10 kV pulsed discharge. This value is derived from charging of insulation blankets and subsequent discharges.

Requirement Lessons Learned (A5.7): A maintenance person was working inside a fuel tank and experienced an arc from his wrench when removing bolts. It was found that maintenance personnel were routinely taking foam mats into the tank to lie on while performing maintenance. Friction between the mat and clothing allowed a charge buildup which caused the arc. All static generating materials should be prohibited from the tank during maintenance.

Many equipment failures have been attributed to ESD damage of electronic parts.

Verification Rationale (A5.7): Verification of protection design for electrostatic charging is necessary to ensure that adequate controls have been implemented.

Verification Guidance (A5.7): The selected verification method must be appropriate for the type of structural material being used and the particular type of control being verified. Relatively poor electrical connections are effective as discharge paths for electrostatic charges. Therefore, inspection would normally be appropriate for verifying that metallic and conductive composite structural members are adequately bonded provided that electrically conductive hardware and finishes are being used. For dielectric surfaces which are treated with conductive finishes, testing of the surface resistivity and electrical contact to a conductive path would be normally be more appropriate.

For space and launch vehicles, ESD requirements are verified by a pulsed discharge at one per second for 30 seconds at a distance of 30 cm to exposed face of subsystems and equipment. This test is then repeated using a direct discharge from the test electrode to each top corner of the equipment under test. The discharge network is 100 pF in series with 1500 ohms.

Verification Lessons Learned (A5.7): To evaluate proper design of structural components, verification that all components are adequately bonded to each other often must be done during system assembly. After manufacturing is completed, access to some components may be restricted making verification difficult.

A5.7.1 Vertical lift and in-flight refueling. *The system shall meet its operational performance requirements when subjected to a 300 kilovolt discharge. This requirement is applicable to vertical lift aircraft, in-flight refueling of any aircraft, and systems operated or transported externally by vertical lift aircraft. Compliance shall be verified by test (such as MIL-STD-331 for ordnance), analysis, inspections, or a combination thereof. The test configuration shall include electrostatic discharge in the vertical lift mode and in-flight refueling mode from a simulated aircraft capacitance of 1000 picofarad, through a maximum of one ohm resistance.*

Requirement Rationale (A5.7.1): Any type of aircraft can develop a static charge on the fuselage from p-static charging effects addressed in section 5.7.2. Aircraft that have the capability for lifting cargo or performing inflight refueling have special operational concerns. In the case of vertical lift, the accumulated charge can cause an arc between the hook and the cargo during pick-up or between the suspended cargo and the earth during delivery. In the case of in-flight refueling, the tanker aircraft can be at one voltage potential and the aircraft to be refueled will be at a different potential, possibly resulting in an arc during mating of the two aircraft. The maximum expected discharge level for either of these cases is 300 kV. The resulting electrical transients can affect both the aircraft and the suspended cargo.

Requirement Guidance (A5.7.1): For vertical lift capability, the requirement should be applied to both the lifting aircraft and the system being lifted. The concern is for the safe and satisfactory operation of the vertical lift system hardware and no degradation or permanent damage of other mission equipment. For in-flight refueling, the requirement should be applied to the equipment and subsystems that are functioning during refueling. Equipment located near the refueling hardware is of primary concern. Potential hazards due to the presence of ignitable fuel vapors also need to be addressed.

For sling loaded ordnance, this requirement is applicable in addition to section 5.7.3. Examples of systems operated externally by vertical lift aircraft are dipping SONAR and apparatus used for helicopter rescue. The discharge occurs for these systems when the item approaches or contacts the surface of the earth or water.

Requirement Lessons Learned (A5.7.1): To protect personnel on the ground from receiving electrical shocks, it is standard practice for rotorcraft to touch the ground with the hook before it is connected to the cargo. As the cargo is lifted, the whole system (aircraft and cargo) will become recharged. Again, when the cargo is lowered to the ground, it must touch the ground to be discharged before handling by personnel. The aircraft system and cargo often see several electrical discharges as the vertical lift process is executed.

During in-flight refueling, pilots have reported seeing arcing between the refueling probe and the fueling basket during mating. These discharges were several inches long. Based on theses observations, the 300 kV number was derived. Aircraft that have experienced discharges from in-flight refueling have had upsets to the navigation system resulting in control problems.

Verification Rationale (A5.7.1): The path of the discharge is somewhat unpredictable. Inspections and analysis are need to verify that assumptions on current flow path are reasonable and that protection is appropriately implemented. Testing is necessary to evaluate possible paths where the discharge event may occur. The 1000 picofarad capacitance used for testing represents a reasonable value for a large size aircraft.

Verification Guidance (A5.7.1): The testing for vertical lift equipment on the aircraft has involved injecting the cargo hook with discharges from a mini-Marx generator. Testing for the in-flight refueling has involved injecting the in-flight refueling probe on the aircraft with discharges from a mini-Marx generator. Both positive and negative discharge voltages have been used for both types of testing. Aircraft equipment are monitored for upset or failure.

Testing of the vertical-lift cargo has involved applying mini-Marx discharges to the shipping container or directly to the cargo system depending upon the configuration used in transport. The container should have discharges applied to several locations around the container. After the discharge, the system is checked for proper operation.

MIL-STD-331 provides guidance on issues with explosive devices and additional background.

Verification Lessons Learned (A5.7.1): Not available.

A5.7.2 Precipitation static (P-static). *The system shall control p-static interference to antenna-connected receivers onboard the system or on the host platform such that system operational performance requirements are met. Compliance shall be verified by test, analysis, inspections, or a combination thereof. For Navy aircraft and Army aircraft applications, p-static protection shall be verified by testing that applies charging levels representative of conditions in the operational environment.*

Requirement Rationale (A5.7.2): As systems in motion encounter dust, rain, snow, and ice, an electrostatic charge buildup on the structure results due to precipitation static charging. This buildup of static electricity causes significant voltages to be present which can result in interference to equipment and constitute a shock hazard to personnel. For aircraft applications, aircrew personnel may be affected during flight and ground personnel may be affected after landing.

Requirement Guidance (A5.7.2): Static electricity accumulates on aircraft in flight (p-static charging) since there is no electrical path for the charges to flow to ground. Special control mechanisms become necessary. The developed voltage on an aircraft with respect to the surrounding air becomes high enough that the air periodically breaks down in an impulse fashion at sharp contour points where the electric field is the highest. The sharp impulses produce broadband radiated interference which can degrade antenna-connected receivers. The impulses can occur so rapidly that the receivers produce only a hissing sound and become useless. Precipitation static dischargers are usually used to control this effect. These devices are designed to bleed the accumulated charge from the aircraft at levels low enough not to cause receiver interference.

The total charging current (I_t - μA) is dependent on charging current densities (I_c - μA/m^2) related to weather conditions, the frontal surface area (S_a - m^2) of the aircraft, and the speed of the aircraft (V - knots). The total charging current can be estimated by the following equation:

$$I_t = I_c \times S_a \times V / 600$$

The following current densities have been determined for various types of clouds and precipitation:

Cirrus	50 to 100 μA/m^2
Strato-cumulus	100 to 200 μA/m^2
Snow	300 μA/m^2

On rare occasions, levels as high as 400 μA/m^2 have been observed.

Control of static charge accumulation is accomplished by ensuring that all structural surfaces are at least mildly conductive (megohms). Conductive coatings need to be applied to all external sections of the system structure which are electrically non-conductive. Any component of the structure can accumulate an electrostatic charge, and adequate means must be provided to dissipate the charge at low levels to prevent any significant voltage from developing.

Requirement Lessons Learned (A5.7.2): A fighter aircraft was experiencing severe degradation of the UHF receiver when flying in or near clouds. Investigation revealed that the aircraft was not equipped with precipitation static dischargers. Installation of these devices solved the problem.

An aircraft had a small section of the external structure made of fiberglass. Post-flight inspections required personnel to get in close proximity to this non-conductive structural component. On several occasions, personnel received significant electrical shocks which caused them to fall from ladders and be injured. Corrective action was easily accomplished be applying a conductive paint to the surfaces exposed to airflow and personnel contact.

Static discharges from the canopy were shocking pilots on a fighter aircraft during flight. Charges accumulating on the outside of the canopy apparently migrated slowly through the dielectric material and discharged to the pilot's helmet when sufficient charge appeared on the inside surface. A grounded conductive finish on the inside of the canopy fixed the problem. Experience with an ungrounded conductive finish aggravated the problem.

When an aircraft was flying in clouds during a thunderstorm, the pilot was unable to transmit or receive on the communications radio. Further investigations were performed with the most reasonable conclusion that the radio blanking was caused by electrostatic discharge. Several incidents were also reported where pilots and ground crews received shocks due to static discharges from aircraft canopies. These incidents occurred on the carrier deck after the aircraft had been airborne for several hours.

It was discovered on an aircraft that was experiencing p-static problems that the static dischargers had been installed using an adhesive that was not electrically conductive.

Verification Rationale (A5.7.2): Systems, subsystems and equipment must be verified to not pose a hazard when subjected to p-static charging. Conductive coating resistance must be verified to fall within the given range so as to not cause an excessive accumulation of electrostatic charge.

Verification Guidance (A5.7.2): Relatively poor electrical connections are effective as discharge paths for electrostatic charging. Therefore, inspection would normally be appropriate for verifying that metallic and conductive composite structural members are adequately bonded provided that electrically conductive hardware and finishes are being used. A device capable of measuring surface resistance within the given range should be used to test the resistance of the coated area.

Testing hardware which applies electrical charge to system surfaces must be able to isolate and identify corona sources, locate isolated metal, identify surface streamering problems, and allow for evaluation of effects to antenna-connected receivers.

Verification Lessons Learned (A5.7.2): Coordination between structural and electrical engineer personnel is necessary to ensure that all required areas are reviewed. For example, a structural component on an aircraft was changed from aluminum to fiberglass and experienced electrostatic charge buildup in flight which resulted in electrical shock to ground personnel. The structural engineer made this change without proper coordination, which resulted in an expensive modification to correct the shock problem.

A5.7.3 Ordnance subsystems. *Ordnance subsystems shall not be inadvertently initiated or dudded by a 25 kilovolt electrostatic discharge caused by personnel handling. Compliance shall be verified by test (such as MIL-STD-331), discharging a 500 picofarad capacitor through a 500 ohm resistor to the ordnance subsystem (such as electrical interfaces, enclosures, and handling points.*

Requirement Rationale (A5.7.3): Explosive subsystems are used for many purposes including store ejection from aircraft, escape systems, rocket motors, and warhead initiation. Voltages and discharge energies associated with ESD can inadvertently ignite or fire these devices. The consequences can be hazardous.

Requirement Guidance (A5.7.3): This requirement is based on charge levels that could possibly be developed on personnel. All explosive subsystems should meet this requirement to guarantee safe personnel handling.

Requirement Lessons Learned (A5.7.3): Explosive subsystems have been initiated by ESD caused from human contact or other sources of ESD.

Verification Rationale (A5.7.3): Due to the safety critical nature of maintaining explosive safety, the high confidence provided by testing is necessary to ensure that requirements are met.

Verification Guidance (A5.7.3): During testing, circuit inductance should be limited to 5 microhenries.

The 500 picofarad capacitor and 500 ohm resistor simulate the characteristics of a human body discharge. A significant number of components must be tested to provide a statistical basis for concluding that the requirement is met. For EIDs, the discharges must be applied in both pin-to-pin and pin-to-case modes for both polarities.

Verification Lessons Learned (A5.7.3): A ground launched missile being removed from a container exploded. It was hypothesized the accident could have been caused by an electrostatic discharge to the propellant (not to the EID).

A5.8 Electromagnetic radiation hazards (EMRADHAZ). *The system design shall protect personnel, fuels, and ordnance from hazardous effects of electromagnetic radiation. Compliance shall be verified by test, analysis, inspections, or a combination thereof.*

Requirement Rationale (A5.8): It has been firmly established that sufficiently high electromagnetic fields can harm personnel, ignite fuel, and fire electrically initiated devices (EIDs). Precautions must be exercised to ensure that unsafe conditions do not develop.

Requirement Guidance (A5.8): See guidance for 5.8.1, 5.8.2, and 5.8.3.

Requirement Lessons Learned (A5.8): See lessons learned for 5.8.1, 5.8.2, and 5.8.3.

Verification Rationale (A5.8): See rationale for 5.8.1, 5.8.2, and 5.8.3.

Verification Guidance (A5.8): Guidance is provided below under sections 5.8.1, 5.8.2, and 5.8.3.

Verification Lessons Learned (A5.8): Lessons learned are provided below under sections 5.8.1, 5.8.2, and 5.8.3.

A5.8.1 Hazards of Electromagnetic Radiation to Personnel (HERP). *The system shall comply with current national criteria for the protection of personnel against the effect of electromagnetic radiation. DoD policy is currently found in DoDI 6055.11. Compliance shall be verified by test, analysis, or combination thereof.*

Requirement Rationale (A5.8.1): One of the potential effects of personnel exposure to electromagnetic fields is heating of the human body. The fact that heating is associated with absorption of RF power by humans was known nearly 50 years ago and led to the introduction of RF diathermy for medical and surgical purposes. The heat from RF field interactions simply adds to the metabolic heat load of the human. If the body's heat gain exceeds its ability to rid itself of excess heat, the body temperature rises. Therefore, if significant RF power is absorbed, an increase in body temperature is expected which could have a competing effect on metabolic processes, with potentially deleterious effects.

Requirement Guidance (A5.8.1): DoDI 6055.11 implements this HERP criteria for military operations.

Requirement Lessons Learned (A5.8.1): Radar and electronic countermeasures (ECM) systems usually present the greatest potential personnel hazard due to high transmitter output powers and antenna characteristics and possible exposure of servicing personnel.

Personnel assigned to repair, maintenance, and test facilities have a higher potential for being overexposed because of the variety of tasks, the proximity to radiating elements, and the pressures for rapid maintenance response.

Verification Rationale (A5.8.1): Safety regarding RF hazards to personnel must be verified.

Verification Guidance (A5.8.1): DoDI 6055.11 provides detailed methodology for assessing hazards.

An RF hazard evaluation is performed by determining safe distances for personnel from RF emitters. Safe distances can be determined from calculations based on RF emitter characteristics or through measurement. Once a distance has been determined, an inspection is required of areas where personnel have access together with the antenna's pointing characteristics. If personnel have access to hazardous areas, appropriate measures must be taken such as warning signs and precautions in servicing publications, guidance manuals, operating manuals, and the like.

Verification Lessons Learned (A5.8.1): Safe distance calculations are often based on the assumption that far-field conditions exist for the antenna. These results will be conservative if near-field conditions actually exist. Air Force TO 31Z-10-4 and Navy OP 3565 provide techniques for calculating the reduction of gain for certain types of antennas. Measurements may be desirable for better accuracy.

Before a measurement survey is performed, calculations should be made to determine distances for starting measurements to avoid hazardous exposures to survey personnel and to prevent damage to instruments. Since hazard criteria are primarily based on average power density and field strength levels (peak levels are also specified), caution needs to be exercised with the probes used for measurements because they have peak power limits above which burnout of probe sensing elements may occur.

When multiple emitters are present and the emitters are not phase coherent (the usual case), the resultant power density is additive. This effect needs to be considered for both calculation and measurement approaches.

In addition to the main beam hazard, localized hot spots may be produced by reflections of the transmitted energy from any metal structure. These results can occur in areas having general power densities less than the maximum permissible exposure limits.

Experience has shown aboard ships, that unless personnel observe the restrictions (clear zones) around emitting radiators, personnel can be affected by extensive exposure to electromagnetic radiation.

A5.8.2 Hazards of electromagnetic radiation to fuel (HERF). *Fuels shall not be inadvertently ignited by radiated EMEs. The EME includes onboard emitters and the external EME (see 5.3). Compliance shall be verified by test, analysis, inspection, or a combination thereof.*

Requirement Rationale (A5.8.2): Fuel vapors can be ignited by an arc induced by a strong RF field.

Requirement Guidance (A5.8.2): The existence and extent of a fuel hazard are determined by comparing the actual RF power density to an established safety criteria. TO 31Z-10-4 and OP 3565 provide procedures for establishing safe operating distances.

RF energy can induce currents into any metal object. The amount of current, and thus the strength of a spark across a gap between two conductors, depends on both the field intensity of the RF energy and how well the conductors act as a receiving antenna. Many parts of a system, a refueling vehicle, and static grounding conductors can act as receiving antennas. The induced current depends mainly on the conductor length in relation to the wavelength of the RF energy and the orientation in the radiated field. It is not feasible to predict nor control these factors. The hazard criteria must then be based on the assumption that an ideal receiving antenna could be inadvertently created with the required spark gap.

Requirement Lessons Learned (A5.8.2): There is a special case where a fuel or weapon RF hazard can exist even though the RF levels may be within the safe limits. This special case is for both the hand-held (1-5 watts) and mobile (5-50 watts) transceivers. The antennas on this equipment can generate hazardous situations if they touch the system, ordnance, or support equipment. To avoid this hazard, transceivers should not be operated any closer than 10 feet from ordnance, fuel vents, and so forth.

Verification Rationale (A5.8.2): Safety regarding RF hazards to fuels must be verified. A majority of the verification is done by inspection and analysis with testing limited to special circumstances.

Verification Guidance (A5.8.2): TO 31Z-10-4 and OP 3565 provide methodology for calculating hazard distances from RF emitters. An important issue is that fuel hazard criteria are usually based on peak power, while hazard criteria for personnel are based primarily on average power. Any area in the system where fuel vapors may be present needs to be evaluated. Restrictions on use of some RF emitters may be necessary to insure safety under certain operations such as refueling operations. Any required procedures must be carefully documented in technical orders or other appropriate publications.

The volatility and flash point of particular fuels influence whether there is a hazard under varying environmental conditions.

Verification Lessons Learned (A5.8.2): See lesson learned for section 5.8.1.

A5.8.3 Hazards of electromagnetic radiation to ordnance (HERO). *Ordnance with electrically initiated devices (EIDs) shall not be inadvertently ignited during, or experience degraded performance characteristics after, exposure to the external radiated EME of Table IA for either direct RF induced actuation or coupling to the associated firing circuits. Compliance shall be verified by system, subsystem, and equipment level tests and analysis. For EME's in the HF band derived from near field conditions, verification by test shall use transmitting antennas representative of the types present in the installation.*

Requirement Rationale (A5.8.3): RF energy of sufficient magnitude to fire or dud EIDs can be coupled from the external EME via explosive subsystem wiring or capacitively coupled from nearby radiated objects. The possible consequences include both hazards to safety and performance degradation. Table IA represents a maximum composite of Navy mainbeam, Army aviation land-based, and world-wide civilian aircraft certification EME levels.

Requirement Guidance (A5.8.3): Ordnance includes weapons, rockets, explosives, EIDs themselves, squibs, flares, igniters, explosive bolts, electric primed cartridges, destructive devices, and jet assisted take-off bottles.

The accidental firing of EIDs by RF energy is not a new concern. Commercial manufacturers of blasting caps have warned their customers for many years about the potential hazard involved in using electrically fired blasting caps in the vicinity of radio transmitters. Most EIDs employ a small resistive element called a bridgewire. When the EID is intentionally fired, a current pulse is passed through the bridgewire, causing heating and resultant initiation of the explosive charge. RF induced currents will cause bridgewire heating that may inadvertently fire the EID. Interface wiring to the EID generally provides the most efficient path for RF fields to couple energy to the bridgewire. However, RF energy can also fire extremely sensitive devices, such as electric primers, as a result of capacitive coupling from nearby radiated objects. RF energy may also upset energized EID firing circuits, causing erroneous firing commands to be sent to the EID. Non-bridgewire types of EIDs are being increasingly used for many ordnance applications. The electrothermal behavior of these devices differs considerably from bridgewire devices; many have much faster response times and exhibit non-linear response characteristics.

EIDs should be the least sensitive that will meet system requirements.

Each EID must be categorized as to whether its inadvertent ignition would lead to either safety or performance degradation problems. This categorization should be determined by the procuring activity.

OD 30393 provides design principles and practices for controlling electromagnetic hazards to ordnance. MIL-STD-1576 provides guidance on the use and test of ordnance devices in space and launch vehicles.

Requirement Lessons Learned (A5.8.3): The response of an EID to an RF energy field, and the possibility of detonation, depend on many factors. Some of these factors are transmitter power output, modulation characteristics, operating frequency, antenna propagation characteristics, EID wiring configuration (such as shielding, length, and orientation) and the thermal time constant of the device.

Several incidences onboard Navy ships involving the inadvertent firing of rockets and missiles have resulted in catastrophic loss of life and equipment.

There have been numerous explosive mishap reports involving RF induced, uncommanded actuation of automatic inflators worn by aircrew personnel both on flight decks and in-flight while launching from and landing on the carrier. These problems pose a tremendous hazard to aircrews, especially those in-flight at the time of occurrence.

Use of uncertified systems onboard ships due to joint operations has resulted in operational restrictions on shipboard emitters.

Verification Rationale (A5.8.3): Adequate design protection for electroexplosive subsystems and EIDs must be verified to ensure safety and system performance. Unless a theoretical assessment positively indicates that the pick-up on EID firing lines or in electronic circuits associated with safety-critical functions is low enough to assure an acceptable safety margin in the specified EME (bearing in mind the possible inaccuracies in the analysis technique), it will be necessary to conduct a practical test.

Verification Guidance (A5.8.3): Verification methods must show that electroexplosive subsystems will not inadvertently operate and EIDs will not inadvertently initiate or be dudded during handling, storage, or while installed in the system. Assessment of the immunity of an EID is based upon its no-fire threshold. For acceptance, it must be demonstrated that any pick-up in an EID circuit in the specified EME will not exceed a given level expressed as a margin in dB below the maximum no-fire threshold sensitivity for the EID concerned. The maximum no-fire threshold is defined in terms of the level at which no more than 0.1% of the devices will fire at a 95% confidence level when a stimulus is applied for a period of time at least ten times the time constant of the device. The maximum no-fire threshold can also be defined in accordance with MIL-I-23659. Furthermore, there must not be any RF-induced interference to energized firing circuits that results in an unintentional firing command or stimulus to the EID in the specified EME. Acceptable performance is demonstrated as the margin in dB below the malfunction or switching threshold for an electronic component or system.

The required margins, as specified in section 5.1, distinguish between safety (16.5 dB) and other applications (6 dB) and allow for measurement uncertainties, such as test instrumentation, EME levels, system configuration, and so forth.

There are several issues associated with margins during testing.

a. Instrumented tests are preferred over uninstrumented tests. However, in some cases where instrumentation cannot be used to monitor the response of the EID or associated firing circuits, “go or no-go” testing is the only alternative. Overtesting as discussed below may be necessary when “go or no-go” techniques are used.

b. Direct inject tests can be used to achieve “overtest” conditions and thus demonstrate acceptable margins for uninstrumented EIDs and non-linear firing circuits. However, this requires an *a priori* knowledge of the transfer function relating currents flowing into the EID or firing circuit wiring to specified radiated EME levels. RF currents can be injected directly into the EID or firing circuit wiring to determine whether the EID will fire. Acceptable performance is indicated by non-initiation of the EID when the injected current levels exceed those associated with the specified EME by the indicated margins.

c. Overtesting to demonstrate acceptable margins can also be accomplished using radiated levels in excess of the specified EMEs (if the capacity to generate these levels exists), removing shielding and filtering protection, or using special test procedures to enhance RF coupling into the EIDs and firing circuits. In all cases, the degree of overtest should be quantitatively determined to verify that the required margins can be demonstrated. The procuring activity should approve any such methods.

When the available test EME levels are less than the specified EME levels, the absence of observed firing circuit susceptibility only assures acceptable performance at or below the available test levels. Performance of non-linear circuits and devices at the (higher) specified EMEs should not be predicted on the basis of linear extrapolation.

HERO testing should include exposure of the ordnance to the test EME in all life cycle configurations, including packaging, handling, storage, transportation, checkout, loading and unloading, and launch. The system should be exposed to the test EME while being exercised with operating procedures associated with those configurations. For system configurations exclusively involving the presence of personnel, such as assembly and disassembly or loading and downloading, the levels in Table IA may be lowered to the levels found in the applicable personnel hazards criteria. (section 5.8.1).

Methods used to demonstrate compliance with HERO requirements require instrumenting the EID and firing circuits using techniques such as thermocouple and fiber optic temperature sensors, RF voltage or current detectors, temperature sensitive waxes, or substitution of more sensitive elements. Such instrumentation must not alter the system’s inherent (non-instrumented) response characteristics. The instrumentation’s sensitivity and response time must be sufficient to capture maximum RF-induced responses of the EIDs or firing circuits at specified EMEs.

The test EME should simulate the specified EME to the extent necessary to stimulate maximum EID and firing circuit responses. This requires an appropriate representation of the specified EME with respect to frequency, field strength (power density), field polarization, and illumination angle. For radar EMEs, representative pulse widths, pulse repetition frequencies, and beam dwell periods should be chosen to maximize system response with due consideration for the response times of EIDs and firing circuits. In the HF range, transmitting antennas should be the same type used to produce the service EME.

Determination of system resonances is fundamental aspect of HERO testing. Where possible, swept-frequency testing is the preferred means of determining resonance frequencies. Mode-stirred (reverberation) chambers can be used effectively for creating contained, swept-frequency EMEs. Follow-on testing at discrete, high level EMEs is recommended to determine actual radiated susceptibility thresholds. In the absence of preliminary swept frequency resonance identification, Table AII provides the recommended minimum number of frequencies for discrete frequency testing.

In cases where the test EME is less than the specified EME, the response of linear devices (such as bridgewire EIDs) can be extrapolated to reflect the response in the higher specified EME. However, when there is no detected response with the given test EME, the following restriction on extrapolation is necessary: the acceptable EME should not be increased by a factor exceeding the ratio of the pass or fail limit to instrumentation sensitivity. The response of non-linear EIDs (such as semiconductor junction devices and electronic safe and arm devices) should not be extrapolated.

MIL-STD-1576 provides guidance on verifying ordnance requirements for space systems. Statistical Research Group report No. 101-R, SRG-P, No. 40 provides evaluation methods for ordnance. Franklin Institute report M-C2210-1 provides analysis techniques.

TABLE AII. Recommended number of test frequencies

Frequency Band (MHz)	Minimum Number of Test Frequencies per Band
0.01 - 2	10
2 - 32	20
32 - 100	20
100 - 1,000	10
1,000 - 18,000	20
18,000 - 40,000	5

Verification Lessons Learned (A5.8.3): There are a number of concerns with EIDs and instrumentation techniques. The influence of the instrumentation on the normal thermal and electrical characteristics of the EID must be minimized. Even the removal of the explosive powder for both safety and instrumentation reasons will have some effect on heating and electrical characteristics due to changes in thermal capacity and dielectric properties. Devices with greater sensitivity used in place of the EID must have characteristics as close as possible to the EID, including electrical wiring and lead construction. Similarity of RF impedance and response times of substitution devices should be verified, if possible, by measurement.

An important parameter, which often does not receive adequate attention in safety evaluations, is the thermal time constant of the EID. The temperature rise of EID bridgewires to a current step can be modeled as an exponential. The time constant is the point in time on an exponential curve where the exponent equals minus one and 63% of the final temperature value has been reached. LA-5201-MS reports on a detailed study of EID characteristics which found typical time constants for bridgewire devices to be between 1 and 20 milliseconds. Heating and cooling time constants are similar. Time constants are not routinely determined as standard practice.

Most instrumentation techniques in use are slow responding, particularly with respect to 1 millisecond. They will produce reasonable results for high duty cycle waveforms such as voice communications. For pulsed radar signals, these techniques rely on a long-term effect called thermal stacking, which is related to average power. Each pulse causes a small amount of heating followed by a relaxation period where some cooling occurs. After several thermal time constants, the temperature of the EID bridgewire reaches an equilibrium condition with some small temperature excursions about the equilibrium point.

This concept works well when the pulse width and pulse period are small compared with the time constant, for example, a 1 microsecond pulse and a 1 millisecond period with a 20 millisecond EID time constant. However, radars exist with pulse widths well over 1 millisecond and pulse rates may be low or not even relevant due to phased-array operation where consecutive pulses may be at completely different azimuth and elevation positions. Some examples follow. If a radar has a 5 millisecond pulse width and a 1 millisecond time constant EID is under consideration, the thermal element will essentially reach equilibrium during a single pulse and average power is irrelevant. The radar can be treated as continuous wave. If the radar has a 20 millisecond inter-pulse period (50 Hz pulse repetition frequency), a 1 millisecond thermal element will cool completely between pulses for practical purposes and no thermal stacking takes place. Under this condition, the energy in the pulse is important for pulses which are short compared to the time constant, and the peak power is important for pulses which are long compared to the time constant. Most present instrumentation will not provide reliable results for these situations, and analytical techniques or special calibrations may be necessary to correct results.

EIDs with thermal response times less than or equal to the radar pulse width are referred to as "pulse-sensitive" or "peak power-sensitive" devices. Examples include conducting composition devices, thin film devices, and semiconductor junction devices.

When the thermal time constant of an EID is known, calculations can be made to assess responses for varying emitter parameters. If the response of an EID is known for CW or, equivalently, for a pulse that is long compared to the thermal time constant ($\geq$ 10 times the time constant), a meaningful response figure for a particular pulsed emitter can be obtained by using the following multiplying factor (MF) for peak power in the pulse.

$$\mathrm{MF} = \frac{(1 - e^{-t_2/\tau})}{(1 - e^{-t_1/\tau})}$$

where t_1 = radar pulse width
t_2 = radar pulse interval = 1/PRF (pulse repetition frequency)
τ = EID time constant

For example, if an EID with a 100 μsec time constant has a maximum no-fire power of 1 watt CW at the operating frequency of a radar with a 30 μsec pulse width and 1000 μsec pulse interval, the MF is:

$$\mathrm{MF} = \frac{(1 - e^{-1000/100})}{(1 - e^{-30/100})} = 3.86$$

Therefore, the maximum no-fire level for the EID for peak pulse power is 3.86 watts. Similarly, the MF can be used with known responses from radiated fields. If the installed EID is known to be capable of tolerating 100 mW/cm^2 for a CW field, then it is reasonable to assume it can tolerate 386 mW/ cm^2 peak power density for the particular radar. Similar calculations can be made to compare peak electric fields, voltages and currents to CW parameters; however, the square root of MF must be used to obtain correct values. If a 16.5 dB margin exists for the CW field, then the same 16.5 dB margin exists for the calculated pulsed field.

When the EID time constant is short compared to both the emitter pulse width and pulse interval, the MF approaches one as expected indicating that a single emitter pulse has the same effect as CW.

For space applications using ordnance devices, an analysis of margins based in the RF threshold determination of the MNFS should be performed.

A5.9 Life cycle, E^3 hardness. *The system operational performance and E^3 requirements of this standard shall be met throughout the rated life cycle of the system and shall include, but not be limited to, the following: maintenance, repair, surveillance, and corrosion control. Compliance shall be verified by test, analysis, inspections, or a combination thereof, of system design features. Maintainability, accessibility, and testability, and the ability to detect degradations shall be demonstrated.*

Requirement Rationale (A5.9): Advanced electronics and structural concepts are offering tremendous advantages in increased performance of high-technology systems. These advantages can be seriously compromised, however, if E^3 protection concepts impact life cycle costs through excessive parts count, mandatory maintenance, or costly repair requirements. It is essential, therefore, that life-cycle considerations be included in the tradeoffs used to develop E^3 protection.

Corrosion control is an important issue in maintaining EMC throughout the system’s life cycle.

It is important that protection provisions that require maintenance be accessible and not be degraded due to maintenance actions on these provisions.

Requirement Guidance (A5.9): There are normally a number of approaches available for providing E^3 protection. The particular design solution selected must give adequate consideration to all aspects of the life cycle including maintenance and need for repair.

E^3 hardening features should either be accessible and maintainable or should survive the design lifetime of the system without mandatory maintenance or inspection. Protection measures which require maintenance should be repairable or replaceable without degradation of the initial level of protection. The system design should include provisions to restore the effectiveness of bonding, shielding, or other protection devices which can be disconnected, unplugged, or otherwise deactivated during maintenance activities.

E^3 protection schemes include specific design measures both internal to electrical and electronic enclosures and in the basic system structure. Factors such as corrosion, electrical overstress, loose connections, wear, misalignment, dirt, paint, grease, sealant, and maintenance actions will degrade the effectiveness of some protection measures with time.

To ensure continued protection (hardness) throughout the system life-cycle, protection schemes and devices must be identified and maintenance intervals and procedures specified. Emphasis needs to be placed on critical functions for system operational and mission performance. The user must assume the responsibility to maintain the hardness for the life of the system and to modify procedures as necessary to include conditions not originally anticipated. Maintenance publications should document required actions. Some of the design features affecting hardness are overbraiding of electrical cables, integrity of shielded volumes, electrical bonding of surfaces, linear (resistance, capacitance and inductance) and non-linear (such as transzorbs, zener diodes, and varistors) filtering, circuit interface design (balance, grounding, and so forth), and circuit signal processing characteristics.

Maintenance actions must also be addressed which are performed on non-critical items which are in the same area as the critical items to ensure that personnel do not inadvertently compromise the protection measures of the critical functions. Procedures addressing modifications to the system which involve either new or existing subsystems which perform critical functions must be considered. They could also involve modifications to the system structure or subsystem components, such as wiring and protective devices.

E^3 maintenance should be integrated into normal system maintenance and repair cycles. Separate independent maintenance is undesirable.

Electromagnetic design features that require scheduled maintenance shall be accessible so they can be tested or inspected.

In deployment, space-based equipment cannot be routinely inspected or serviced. Therefore, the space vehicle must have features that are designed for unattended operation and durability for the life of the mission.

Requirement Lessons Learned (A5.9): Many times in the past, E^3 protection has been installed without sufficient thought being given to maintenance and repair. It is often very difficult to access protection measures to determine if they are still effective. By considering the problem of access and test during design, it can be relatively simple to provide protection measures which will allow maintenance checks to be made while minimizing any negative impacts to the design. Also, design techniques oriented toward better maintenance access can provide capability for quality control checks during assembly, benefiting both the system manufacturer and user.

“Don't design it if it can't be repaired." Protection must be designed so as to be easily repairable. The protection system and any repair details must be appropriately documented. For example, if lightning diverter strips or buttons are used on radomes, the maintenance information must reflect any precautions, such as not painting. If fuel tank skins should not be painted to prevent puncture by lightning, this information must be documented with rationale.

Some key areas which require special consideration are addressed in the sections below.

Access doors made of composite materials which are an element of the shielding for a volume are generally designed to be bonded electrically to the system structure. If door spring fingers are employed, they must be kept clean, free from damage, and aligned at all times. Good contact between the door frame around the access door and the spring fingers is critical for maintaining shielding integrity. The bonding area must be inspected to ensure that the bonding effectiveness has not been degraded by dirt, corrosion, sealant and paint overruns, damage, or misalignment.

Screens using wire mesh have been used to shield openings in structure. These screens need to be treated in a fashion similar to the access doors.

Effective electrical bonding of electrical and electronic enclosures to system structure is often essential for proper operation in the various electromagnetic environments. Surfaces on the enclosures and structure must be kept clean to maintain proper bonding. Documentation associated with the system should clearly show areas needed for bonding and the appropriate finishes which should be on the surfaces. Painting of areas intended for electrical bonding has been a common cause of EMC problems. An example of bonding design is the contact between the back of an enclosure and the finger washers in the rear wall of the electronics rack. Other electrical bonds which require attention may be in the form of flat bands or braids across shock mounts or structural members.

It is important that replacement hardware conform to the original design concept. For example, when damaged cables are repaired, shield termination techniques established for the design must be observed.

An example of a subtle change in hardware configuration to the original design concept can be found in a life vest. The life vest was fielded with an bridgewire EID that could be fired by a salt-water activated battery pack that had been hardened and certified for HERO. After introduction into the fleet, an engineering change proposal was developed, and approved, to modify the type of battery used in the battery pack. The change was not submitted for HERO consideration. When the life vests were equipped with the new battery pack and used on board Navy ships, there were reports of uncommanded activation of the vests during flight operations and on the flight deck. The subsequent investigation found that the new battery pack made the EID subsystem resonant to a ship radar system; thereby, creating susceptibility problems.

Verification Rationale (A5.9): Compliance with life cycle requirements must be verified to ensure that E^3 protection can be maintained and does not degrade with time. Verification can range from inspection of proper documentation to actual demonstration of techniques.

Verification Guidance (A5.9): Some E^3 protection measures, such as electrical contact of critical components and electromagnetic shielding effectiveness, cannot be maintained by visual inspections alone. Some testing will probably be necessary; however, the need for any hardness surveillance testing should be minimized as much as possible.

The techniques and time intervals for evaluating or monitoring the integrity of the system protection features need to be defined. The user will probably need to adjust the maintenance intervals after attaining experience with the degradation mechanisms. BIT capability, test ports, resistance measurements, continuity checks, transfer impedance measurements, and transfer function measurements are some of the means available for use in the periodic surveillance of system integrity. For evaluation of possible degradation, a baseline of the system as delivered to the user is necessary.

Verification Lessons Learned (A5.9): The manufacturer of the system has the best understanding of the system protection measures. His role in defining appropriate requirements for various protection measures in a manner which can be effectively verified at the system-level and evaluated during maintenance is key to a successful life cycle program. These considerations include the need for easy access to protection measures requiring evaluation. Otherwise the performance of some protection measures may be neglected. In some cases, other system design considerations may be overriding. In such cases, it is often possible to provide features in the design (such as test tabs or special connectors) which will permit a test measurement to be made without time-consuming disassembly.

Most shielded cable failures occur at the connector and a resistance meter capable of measuring milliohms is usually sufficient for locating these failures. Testing on several aircraft has shown that holes or small defects in the shields themselves are not a significant problem. It takes major damage to the shield for its effectiveness to be degraded. In addition, time domain reflectometers can be used to locate discontinuities or changes in protection schemes. Measurements after the system is fielded can be compared to baseline measurements.

Cable shield testers are available for more thorough evaluation of shield or conduit performance. A current driver is easily installed on the outside of the cable; however, a voltage measurement on wires internal to the shield requires access to these wires. If an electrical connector is sufficiently accessible, the voltage measurement is straightforward. In some cases, cables pass through bulkheads without the use of connectors and access is not readily available. A possible solution is to include a pick-off wire attached to one of the wires within the bundle which is routed to a connector block accessible to technicians.

An aperture tester can be used to monitor the integrity of RF gaskets and screens protecting apertures on the system. An existing tester uses a stripline on the outside of the system structure to drive a current across the aperture and the voltage developed across the aperture within the structure is measured. The installation of the stripline has not been difficult; however, paint and non-conductive materials on the inside of structure have hampered the ability to measure induced voltages across doors and window frames. Test tabs or jacks would have greatly simplified the measurement.

Frequent performance of surveillance checks after initial deployment can help in refining maintenance intervals by determining degradation mechanisms and how fast degradation develops.

Life cycle considerations must include the fact that systems are often modified soon after they are fielded and frequently throughout their life. Sometimes the modifications are small and can be qualified with a limited effort. Often there are major changes to system structure as well as to the electronics. The addition of major new subsystems can introduce new points of entry for electromagnetic energy into protected areas, and a major requalification of the system may be necessary. Also, if enough small modifications are made over a period of time, the hardness of the system may be in doubt and requalification should be considered.

EMI hardness evaluations under the Navy's Air Systems' EMI Corrective Action Program (ASEMICAP) have shown that the hardness of aircraft is degraded over time. Electrical inspections have shown numerous instances of foreign object damage, excessive chaffing of wires, and improper splicing and terminations. Bonding measurements performed over a ten year period on a Navy fighter aircraft indicates 10-15% out of specification conditions on a new aircraft, 40-60% out of specification conditions on a five year old aircraft and 70-80% out of specification conditions on a ten year old aircraft. These out of specification bonding conditions result in inadequate termination of shields and boxes and degrade shielding effectiveness. During EMC tests, the effects of corrosion and maintenance practices on the EMC design have been noted. For example, composite connectors were incorporated in the pylons of a Navy attack aircraft to correct a severe corrosion problem on the existing aluminum connectors. The composite connectors are more resistant to the corrosion than aluminum. They do, however, oxidize and produce a powdery residue on the connector. The maintenance personnel would then wire brush this residue, thereby eliminating the outer conductive coating, severely degrading the connector conductivity, and introducing potentially more severe corrosion problems.

A5.10 Electrical bonding. *The system, subsystems, and equipment shall include the necessary electrical bonding to meet the* E^3 *requirements of this standard. Compliance shall be verified by test, analysis, inspections, or a combination thereof, for the particular bonding provision.*

Requirement Rationale (A5.10): Good electrical bonding practices have long been recognized as a key element of successful system design. An indicator of the importance of electrical bonding is that the first item often assessed when EMC problems occur is whether the bonding is adequate. Since electrical bonding involves obtaining good electrical contact between metallic surfaces while corrosion control measures often strive to avoid electrical continuity between dissimilar materials, it is essential that the (potentially conflicting) requirements of each discipline be fully considered in the system design.

Systems generally include ground planes to form equipotential surfaces for circuitry. If voltage potentials appear between electronics enclosures and the ground plane due to internal circuitry operation, the enclosure will radiate interference. Similarly, electromagnetic fields will induce voltage potentials between poorly bonded enclosures and the ground plane. These potentials are imposed as common-mode signals on all circuitry referenced to the enclosure. The same two effects will occur for poorly bonded shield terminations.

Without proper bonding, lightning interaction with systems can produce voltages which can shock personnel, ignite fuel through arcing and sparking, ignite or dud ordnance, and upset or damage electronics.

It is essential that system electrical and electronic equipment be provided with adequate voltage levels from prime power sources for proper operation. Electrical fault conditions must not introduce potential fuel or fire hazards due to arcing or sparking from melted or vaporized structural material. Bonding provisions help control voltage drops in power current return and fault paths.

The system design must protect personnel from shock hazards.

Requirement Guidance (A5.10): The role of bonding is essentially to control voltage by providing low-impedance paths for current flow. Unconventional joints should receive special attention to ensure their adequacy, particularly conductive joints in fuel vapor areas. SAE ARP 1870 provides details on electrical bonding concepts for aerospace systems and examples of bonding techniques. MIL-HDBK-419 provides guidance for grounding, bonding, and shielding of land-based facilities, including installed electronic equipment. MIL-STD-1310 provides guidance for electrical bonding onboard ships.

Special attention should be given to the interdependent relationship between electrical bonding and corrosion control. Design techniques for effective corrosion protection, such as the use of finishes which are not electrically conductive, can result in lack of bonding. Conversely, obtaining a good electrical bond can lead to potential corrosion problems, if the bonding is not properly implemented. Detailed corrosion requirements for systems are imposed by other documents, such as MIL-STD-1568 for airborne systems.

While specific bonding levels required to obtain required performance are system dependent, 2.5 milliohms has long been recognized as an indication of a good bond across a metallic interface, particularly aluminum. There is no technical evidence that this number must be strictly met to avoid problems. However, higher numbers tend to indicate that a quality assurance problem may be present and bonding may be degrading or not under proper control. Higher values may be more appropriate for other metals such as stainless steel or titanium. Also, composite materials will exhibit much higher levels and imposed requirements should be consistent with those materials.

Controls need to be implemented in shield termination paths through connector assemblies. A realistic value would be on the order of 10 milliohms from the shield to the electronics enclosure for a cadmium-plated aluminum assembly, with 2.5 milliohms maximum for any particular joint.

Bonding measures for prevention of fuel ignition hazards from electrical fault currents need to address areas with flammable vapors, installed electrical equipment (such as fuel pumps), electrical paths of fault currents, available levels of fault current, and the bonding value necessary for the implemented design architecture to prevent arcing, sparking, and hot spots.

Requirement Lessons Learned (A5.10): Historically, MIL-B-5087 (superseded by this document) first established electrical bonding requirements for aircraft in 1949. Several electrical bonding classes were defined and eventually designated in subsequent revisions as follows:

a. Class A for antenna installation - no bonding resistance specified.

b. Class C for current return path - fault current versus resistance table provided.

c. Class H for shock hazard - 0.1 ohm.

d. Class L for lightning protection - control internal vehicle voltages to 500 volts.

e. Class R for RF potentials - 2.5 milliohms from electronic units to structure.

f. Class S for static charge - 1.0 ohm.

MIL-B-5087 also provided several approved bonding techniques including the specific hardware that was to be used for electrical bonding. This approach was in essence providing the contractor with a bonding design requirement followed by direction on how to achieve the requirement. There were also less obvious requirements in the standard such as a 2.5 milliohm requirement on connector shells, when used to electrically bond shields. Over the years, the 2.5 milliohm class R requirement became synonymous with MIL-B-5087 and was universally accepted as a design requirement for electronic units to vehicle structure. No scientific basis has been found for this 2.5 milliohm requirement other than the fact that it is a value that can be achieved with good metal-to-metal contact. It therefore represents a good design requirement to ensure that positive electrical bonding is included in the design. The rationale behind this class R bond was most likely to assure that the return circuit impedances were kept very low due to the extensive use of single end circuits in that time frame. Modern electronics uses primarily balanced circuits and the need for this low class R bond is less obvious.

Bonding requirements are still important in today’s systems, only from a different perspective. The equipment case to structure class R requirement probably is not important in most instances; however, the 2.5 milliohm is still a good number for several other electrical bonds such as terminating shields to connectors and bonding connector to equipment case. It is also a good value as a design goal where a good bond is needed for other purposes. It mainly requires the designer to design an intentional bonding path.

The other bonding values of MIL-B-5087 for shock protection, current return paths, and static charge are still valid numbers for use today.

Numerous instances of the need for good bonding have been demonstrated. Bonding improvements or corrections have solved many system problems including precipitation static in UHF radios, susceptibility of electronics to external electromagnetic fields, radiation of interference into antenna-connected receivers, and lightning vulnerabilities.

The actual need for certain bonding in a particular application is not easily ascertained. It is dependent on various items such as the shielding topology, type of circuit interfaces, and the use of the enclosure as a ground reference for circuits and filters. For example, a subsystem which is wholly contained (all enclosures and cable interfaces in a continuous unbroken shield) typically does not necessarily require bonding for RF potential control. External currents will remain outside the shield and internal currents will remain inside. This configuration is rare. The increasing use of differential interface circuits makes equipment enclosure-to-vehicle structure bonding less critical since there is better rejection of common-mode noise

In systems using basically metallic structure, the entire vehicle structure forms a ground plane. The introduction of composite materials in structure, which are much less conductive than metals, has created a need in some cases to introduce separate ground planes to maintain adequate control of E^3.

Verification Rationale (A5.10): Verification of protection measures for electrical bonding is necessary to ensure that adequate controls are implemented.

Verification Guidance (A5.10): The electrical bonding area involves a number of different concerns. The particular verification methodology needs to be tailored for the bonding control being assessed. Many elements require more than one form of verification. When bonding values in the several milliohm range or less is required, accurate testing with a four point probe is a necessity. When much higher values are adequate, inspection of surface finishes and mounting techniques supplemented by analysis can be acceptable. Verification that bonding for lightning protection and antenna patterns is adequate generally requires system-level testing. Analysis is an element of assessing structural voltage drops for power returns, fuel ignition hazards, and personnel shock.

Requirements for electrical continuity across external mechanical interfaces on electrical and electronic equipment are normally verified during the development of the equipment. The equipment to structure interface is normally verified at the system-level. A measurement is made from an enclosure surface to the next major assembly. For example, in an installation with an enclosure mounted in a tray, separate measurements would be applicable from the enclosure to the tray and from the tray to structure. The measurement is normally performed with a DC resistance meter. Ideally, the impedance should be maintained as high in frequency as possible. The impedance will normally remain low for enclosures that are hard-mounted to structure. However, for enclosures installations which use bonding straps, such as shock mounts, the impedance of bonding straps will be significant due to the inductance of the strap. A 5:1 length to width ratio or less is generally considered to be necessary for a bonding strap to be effective.

Use of low current and voltage bonding meters, inspection and analysis of bonding paths, and determination of the number of mechanical interfaces in a bonding path are some of the aspects of verification.

Verification of electrical bonding measures for design against electrical shock is primarily achieved by demonstrating that voltage faults to electrically conductive surfaces will not result in hazardous voltages on the surface. These types of faults should normally trip circuit protection equipment.

Verification Lessons Learned (A5.10): The adequacy of much electrical bonding can be evaluated through DC or low frequency AC resistance measurements and inspection. RF measurements can be performed; however, they require more sophisticated instrumentation, can provide misleading results, and are not recommended. DC measurements have proven to provide a good indication of the quality of a bond. An exception where high frequency measurements can be effective is transfer impedance measurements of shielded cables. Under this type of evaluation, a known RF current is driven on the cable shield and the voltage developed along the inside the shield is measured. Electrical bonding levels of shield terminations and connector assemblies are included in the overall measured value.

Bonding meters are normally four point devices which determine the resistance of a bond by driving a known current between two probes and then measuring the voltage drop across the bond with two other probes. Large applied voltages and currents can influence the measurement by burning through contamination that might be on bonding surfaces. It is better to use lower voltage and current devices to determine the value of a bond.

Torque requirements on bolts and screws plays a role in the effectiveness and life-cycle durability of a bond.

Bonding measurements often require that a protective finish be penetrated with electrical probes to obtain good electrical contact. Care should be taken so that a corrosion problem is not introduced.

For lightning protection, metallic structural members (aluminum, steel, titanium, and so forth) provide the best opportunity to achieve an electrical bond on the order of 2.5 milliohms. A bond of this level will limit the induced voltage on system cabling to 500 volts from lightning strike attachments (200 kA) to system structure.

Overpainting of structure for corrosion control prior to ensuring an electrical bond has been documented as the leading cause of poor or ineffective bonds.

P-static testing has found open bonds such as antennas which are electrically isolated from system structure.

A5.10.1 Power current return path. *For systems using structure for power return currents, bonding provisions shall be provided for current return paths for the electrical power sources such that the total voltage drops between the point of regulation for the power system and the electrical loads are within the tolerances of the applicable power quality standard. Compliance shall be verified by analysis of electrical current paths, electrical current levels, and bonding impedance control levels.*

Requirement Rationale (A5.10.1): It is essential that system electrical and electronic equipment be provided with adequate voltage levels from prime power sources for proper operation. Electrical fault conditions must not introduce potential fuel or fire hazards due to arcing or sparking from melted or vaporized structural material.

Requirement Guidance (A5.10.1): Power quality standards, such as MIL-STD-704 for aircraft and MIL-STD-1399, Section 300, for ships, control the supply voltage for utilization equipment within specified limits. The voltage is maintained at a monitoring location termed the “point of regulation” with allowances for voltage drops beyond this point to the input of the utilization equipment. These drops must be controlled through wire conductor type and size selection and current return path design. Most aircraft use structure as the return path for power currents. Bonding provisions must be incorporated to control the impedance of this path.

Requirement Lessons Learned (A5.10.1): Maintaining required voltage levels on metallic aircraft at utilization equipment has not been a problem since the current return paths have low impedance. With increasing use of composites, the need for separate wire returns or implementation of a ground plane becomes a consideration.

Verification Rationale (A5.10.1): Voltage drops present in power current return paths must be evaluated to ensure that electrical power utilization equipment receive power in accordance with power quality standards and to ensure that fuel and fire hazards are avoided.

Verification Guidance (A5.10.1): On most military aircraft, aircraft structure is used as the current return for electrical power. The controls on bonding between structural members, the resistance of structure, and electrical current levels need to be considered. For aircraft which use wired returns, the resistance of the wire is the primary consideration. The location of the point of regulation for the power system also plays a role.

Verification Lessons Learned (A5.10.1): With metallic aircraft, voltage drops through structure are typically very low. Much higher levels are possible with graphite/epoxy structure.

A5.10.2 Antenna installations. *Antennas shall be bonded to obtain required antenna patterns and meet the performance requirements for the antenna. Compliance shall be verified by test, analysis, inspections, or a combination thereof.*

Requirement Rationale (A5.10.2): Good electrical bonding is a key element of successful antenna installation. Poor bonding can result in changes to the desired antenna patterns and degradation of the effective apertures.

Communications antennas such as blade antennas, often become attachment points for lightning. Without proper bonding, lightning can produce voltages which can severely damage antenna-connected equipment.

Antennas are being connected to composite structures via metallic mesh. This “pseudo ground plane” must be capable of conducting lightning induced currents.

Requirement Guidance (A5.10.2): Bonding provisions required to attain adequate antenna patterns and required antenna gains are system dependent. Typically, counterpoises or ground planes associated with antennas are designed to provide negligible impedance at the operating frequencies of the equipment. Additionally, antenna designs that require a low resistance RF path for efficient operation should have a low impedance path of minimum length to the appropriate metallic portion of the antenna.

Requirement Lessons Learned (A5.10.2): Poor bonding of antennas has resulted in degraded operations of communications and navigation equipment. P-static generation at the antenna base has significantly degraded equipment performance for VHF radios. Additionally, severe lightning damage has occurred on blade antennas with a poor ground plane, specifically, on composite panels. Damage has been severe enough as to require replacement of the antenna and the entire panel.

Verification Rationale (A5.10.2): Verification of bonding for antennas is necessary to ensure that adequate antenna patterns and gains are achieved while providing sufficient low impedance paths for currents induced by p-static, RF, and lightning sources.

Verification Guidance (A5.10.2): Verification of bonding measures for antennas is achieved by demonstrating there is a low impedance path between the conducting portions of the antenna and the counterpoise or ground plane. Antenna patterns and gains can be verified in anechoic chambers or in an RF quiet environment.

Verification Lessons Learned (A5.10.2): The adequacy of antenna bonds can be evaluated through antenna pattern measurements, DC resistance measurements, and inspection. AC measurements are desired, however, they require more sophisticated measurement equipment and procedures.

A5.10.3 Electromagnetic interference (EMI). *The system electrical bonding shall provide electrical continuity across external mechanical interfaces on electrical and electronic equipment, both within the equipment and between the equipment and system structure, for control of* E^3 *such that the system operational performance requirements are met. For Navy aircraft and Army aircraft applications, the EMI bonds shall have an interface direct current (DC) resistance of 2.5 milliohms or less for each faying interface between the subsystem or equipment enclosure and the system ground reference. Compliance shall be verified by test, analysis, inspections, or a combination thereof.*

Requirement Rationale (A5.10.3): EMI bonding (formerly designated Class R (Radio frequency) in MIL-B-5087) is necessary to avoid coupling of interference signals present in the system to subsystems. These interference signals may be generated by other subsystems, the external EME, lightning, p-static, power system ground currents, and so forth. The interference signals from subsystems are usually RF noise on power and control circuits that are seen on subsystem grounds. With a low resistance between a subsystem and the rest of the system, potential differences can be controlled to low values. One of the worst case currents is lightning. At 200 kA and 2.5 milliohms, the voltage transient developed is 500 volts, assuming that all the lightning current is flowing across a particular interface. The 2.5 milliohm value has also been shown to be an obtainable resistance between faying surfaces that have been treated with a corrosion inhibitor. The requirement wording therefore addresses each faying surface down to the system ground reference.

Requirement Guidance (A5.10.3): There is a general requirement for all systems to address and implement bonding measures, without specific control levels being stated. An important issue is that bonding be “under control” and at “known levels.” Bonding must not be haphazard or erratic. Repeatability of performance from system to system and over time is critical. Specific control levels are the responsibility of the developing activity.

Given the long history of the use of 2.5 milliohms for this type of bonding and its success, Navy and Army aircraft systems are required to obtain this low resistance. This value allows for equipment to be procured for multi-platform applications.

The 2.5 milliohm value is a good benchmark for applications in other types of systems; however, a higher resistance is acceptable provided system operational performance is met and bonding is under control and consistent.

Requirement Lessons Learned (A5.10.3): Most EMC handbooks contain information on various techniques to obtain a successful EMI “Class R” bond. Specific techniques are not required in this standard to allow a more flexible implementation of bonding. The use of 2.5 milliohms in the past has precluded many EMI problems. On one aircraft, the rudder was found to shake while being subjected to the external environment. The problem was determined to be that the aileron rudder interconnect subsystem was not EMI bonded. Once bonded, the rudder was stable.

Measurements during several years of Navy ASEMICAP tests have revealed equipment EMI bonding measurements that do not always meet the 2.5 milliohm requirement. Extensive E^3 tests afterwards generally have not connected any EMI problems with the degraded bonding. This extensive data base has supported the concept that it is possible under some conditions to exceed 2.5 milliohms and still have adequate E^3 control.

The use of faying surfaces has to be carefully implemented. Normally it is expected that an equipment enclosure will have a faying surface bond to an equipment rack, the equipment rack will have a faying surface bond to a shelf, and the shelf will have a faying surface bond to the structure, which is usually the system ground reference. In this example the bonding is 2.5 for each faying surface with a total resistance to ground of 7.5 milliohms. Any stacking of washers, spacers, or straps in the path are not considered faying surfaces for purposes of determining the allowable path resistance. In many cases, 2.5 milliohms can be achieved from the equipment case to structure by parallel paths (footpads, unpainted surfaces, grounded supports, and so forth).

Verification Rationale (A5.10.3): Testing is required to actually measure a low impedance bond. Inspection of drawings and processes can ensure that bonding provisions are properly implemented. Analysis of the role of bonding in providing overall E^3 protection is necessary.

Verification Guidance (A5.10.3): The first step in verification is to review the bonding implementation to determine the amount of resistance required from the equipment enclosure to the system ground reference. Next an analysis is made of the points where the measurement can be made. Based on the measurement points, the resistance between the two points is calculated using the total of the EMI bonding in the path. When actually performing the measurement, first visually inspect the EMI bonds to verify their presence and proper construction. Then, remove all other connections to the equipment to ensure that only the EMI bonding is being measured and not the equipment safety ground or other grounding provisions.

Verification Lessons Learned (A5.10.3): Bonding meters that use high voltage and current which may arc or burn through contamination in junctions thus giving optimistic readings should be avoided.

When bonding was accomplished as outlined above with the calculation of the total resistance across a number of faying surfaces, a common problem has been avoided of over-designing the bonding. Measurements can be made using a common point on the system for one probe, thereby simplifying the test.

A5.10.4 Shock and fault protection. *Bonding of all exposed electrically conductive items subject to fault condition potentials shall be provided to control shock hazard voltages and allow proper operation of circuit protection devices. Compliance shall be verified by test, analysis, or a combination thereof.*

Requirement Rationale (A5.10.4): Personnel must be protected from hazardous voltages. For circuit protection devices to work properly, bonding must adequate to allow sufficient fault current flow to trip the devices in a timely manner.

Requirement Guidance (A5.10.4): Voltages on conductive surfaces can result from sources such as broken components in assemblies allowing “hot" wiring to contact the housing or from electrically referencing a circuit to the housing (such as capacitive filtering). The requirement addresses any electrically conductive portion of the system which can become “hot” from contact with higher voltage wiring. It is not limited to electrical and electronic housings. MIL-HDBK-454, Guideline 1, suggests protection from voltages in excess of 30 volts rms and DC.

Requirement Lessons Learned (A5.10.4): Powerline filtering arrangements in electronics which isolate the powerline neutral from chassis can result in hazardous voltages on the enclosure if the frame ground is disconnected. Typically, filters will be present on both the high side and the return which will have capacitance to the chassis. If the chassis is floating with respect to earth ground, the capacitors act as an voltage divider for AC waveforms with half the AC voltage present on the case with respect to earth. The value of the capacitors determines the amount of current that may flow.

For circuit protection to work quickly and effectively, fault currents well in excess of the rating of the circuit are necessary. For example, a circuit breaker can take tens of seconds to interrupt a circuit at a current twice its rating.

For fault paths in areas where flammable vapors may be present, such as in fuel tanks, bonding must be adequate to prevent arcing, sparking, and hot spots which may ignite the vapors. A concern in the past has been the possibility of safety wire or debris bridging a bonded joint and providing a secondary parallel path for fault current flow. If this condition is a realistic possibility, the intended bonding path must limit the current in the secondary path to a level sufficient to prevent ignition of vapors.

Verification Rationale (A5.10.4): Some testing will be probably be necessary to evaluate bonds. Analysis will be necessary to determine where potentially hazardous voltages exist and to assess fault conditions.

Verification Guidance (A5.10.4): System elements where potentially hazardous voltages may appear need to be identified. Fault current paths and associated electrical bonding provisions need to be assessed for adequacy. A traditional control level for shock hazard protection contained in MIL-B-5087 and MIL-STD-1310 was 0.1 ohms. This level is somewhat arbitrary but it may be a suitable control for some applications.

Verification Lessons Learned (A5.10.4): The level of bonding necessary to meet this requirement will normally require that four point bonding meters discussed in section 5.10 be used for measurements.

A5.11 External grounds. *The system and associated subsystems shall provide external grounding provisions to control electrical current flow and static charging for protection of personnel from shock, prevention of inadvertent ignition of ordnance, fuel and flammable vapors, and protection of hardware from damage. Compliance shall be verified by test, analysis, inspections, or a combination thereof.*

Requirement Rationale (A5.11): External grounds are necessary to provide fault current paths for protection of personnel from shock hazards and to dissipate static electricity for prevention of hazards to personnel, flammable vapors, ordnance and electronic hardware.

All telecommunications and electronic facilities are inherently referenced to earth by capacitive coupling, accidental contact, and intentional connections. Therefore, “ground” must be looked at from a total system viewpoint, with various subsystems comprising the total facility ground system. The facility ground system forms a direct path of known low impedance between earth and the various power, communications, and other equipments that effectively extends in approximation of ground reference throughout the facility. The facility ground system is composed of an earth electrode subsystem, lightning protection subsystem, fault protection subsystem, and signal reference subsystem.

For safety reasons, both the MIL-STD-188-124 and the National Electrical Code in NFPA 70 require that electrical power systems and equipment be intentionally grounded. Therefore, the facility ground system is directly influenced by the proper installation and maintenance of the power distribution systems. The intentional grounding of electrical power systems minimizes the magnitude and duration of overvoltages on an electrical circuit, thereby reducing the probability of personnel injury, insulation failure, or fire and consequent system, equipment, or building damage.

Requirement Guidance (A5.11): Many portions of a system require a grounding scheme to ensure that a suitable current path is available for sufficient currents to flow in the event of an electrical fault to trip circuit protection devices. All electrically conductive surfaces with which personnel may come in contact need to be bonded to the ground reference to prevent hazardous voltages from appearing on the surfaces during faults and to provide a path for the resultant fault currents to trip the protection devices.

Grounding provisions are often necessary under certain operations to provide a current path to prevent static electricity charges from accumulating, such as during ordnance handling, refueling or other flammable vapor operations, and maintenance actions on sensitive electronics.

Grounding provisions are usually required for munitions that are stored in bunkers while in containers, or when exposed to the elements to reduce static charge buildup during handling. These include munitions-to-container, container-to-ground, and munitions (not in containers)-to-ground.

General Tactical Ground Shelter Grounding Guidance:

The facility ground system connects any metallic element of the associated subsystems to earth by way of an earth-electrode configuration. It establishes a reference potential common to any equipment or subsystem and makes the ground potential available throughout the system. In general, four subsystems comprise the facility ground system and should be addressed during the design and installation of any electrical and electronic equipment, subsystem, and system. Although, it is not possible to have a fixed set of rules governing the grounding of all conceivable electrical or electronic equipment or system configurations, the guidelines presented here should be adapted to the requirement of a particular tactical installation. More detailed guidance is provided in MIL-STD-188-124 and MIL-HDBK-419.

It is important that serious consideration be given to grounding implementation. Proper grounding can have a significant impact on the ability to maintain operations under adverse conditions. This section contains grounding requirements for tactical deployments of mobile equipment. Grounding methods set forth are based not only on implementation considerations but also on complying with specific measured resistance requirements. The tactical deployments of mobile equipments are considered to be of four types: stand-alone equipment, stand-alone shelters, collocated equipments and collocated shelters.

A stand-alone shelter is comprised of equipment housed in a mobile metallic shelter and, typically, is not situated close enough to other equipments to merit construction of a common extensive earth electrode subsystem between its interfacing systems. Power supplied to the shelter may come from a power generator or a commercial source. Interfacing with the shelter may be through the power cable. The need for grounding stand-alone shelters is to provide a ground for: 1) the fault protection subsystem, 2) “bleeding off” static charges or EMI from interfacing signal cables, 3) the signal reference subsystem, and 4) the lightning protection subsystem.

Collocated mobile equipments are equipments operating individually but hosted together within a single transportable enclosure, such as a tarpaulin. Typically, these equipments are not rack mounted and may be situated on the earth. Intra-enclosure communication links may exist among equipments, but normally links are established between an equipment and an external system. Basic operational characteristics of collocated equipments are similar to stand-alone equipments. Grounding requirements are primarily for personnel safety from lightning and power faults.

Collocated shelters are transportable metallic shelters that share common signal or power cables and are classified in two general categories; those located within 8 meters (26.5 feet) of one another, and those located greater than 8 meters from one another. Collocated shelter configurations are typically of an equipment system that must be housed in multiple shelters. Grounding requirements for collocated shelters are required to provide personnel and equipment protection from the effects of lightning and power faults and to provide a reference for signal grounds. Particular consideration must be given to collocated shelters receiving power from the same power source or communicating over inter-shelter signal cables. The need to establish an all encompassing shelter grounding system for collocated shelters situated more than eight meters apart should be a function of ground resistance measurements taken at each shelter site. The ground system of each shelter should be interconnected as shown in MIL-HDBK-419. If noise or other undesirable effects are produced as a result of higher ground resistance differences, the system having the higher resistance can be reduced by use of chemical treatment or enhancement per MIL-HDBK-419.

Fixed prefabricated shelters are generally designed having the major components prefabricated and then assembled on-site into a fixed shelter which can be considered as a fixed facility. As such, it should have its own earth electrode subsystem (ring ground). It should also have a lightning protection subsystem meeting the requirements of MIL-HDBK-419, whenever the shelter is located outside the cone of protection of a higher grounded tower. The shell of metallic prefabricated shelters should be constructed to be electrically continuous and should be grounded to the earth electrode subsystem to bleed off static charges and reduce the effects of interference to C-E equipments and circuits. If metallic and electrically continuous, the skin of a fixed prefabricated shelter may serve as the equipotential plane. If the skin is not metallic or electrically continuous, a separate equipotential plane will be required.

Requirement Lessons Learned (A5.11): Ignition of ordnance and fuel vapors and damage to electronics have all occurred from static discharges.

Verification Rationale (A5.11): To ensure safety, proper use and installation of external grounds for the system must be verified.

Verification Guidance (A5.11): Inspection is appropriate for verification that external grounding provisions have been implemented.

Verification Lessons Learned (A5.11): Installation practices should be reviewed to ensure that corrosion protection is included.

A5.11.1 Aircraft grounding jacks. *Grounding jacks shall be attached to the system to permit connection of grounding cables for fueling, stores management, servicing, maintenance operations and while parked. ISO 46 contains requirements for interface compatibility. Grounding jacks shall be attached to the system ground reference so that the resistance between the mating plug and the system ground reference does not exceed 1.0 ohm DC. The following grounding jacks are required:*

a. Fuel nozzle ground. A ground jack shall be installed at each fuel inlet. To satisfy international agreements for interfacing with refueling hardware, the jack shall be located within 1.0 meter of the center of the fuel inlet for fuel nozzle grounding.

b. Servicing grounds. Ground jacks shall be installed at locations convenient for servicing and maintenance. For Navy and Army aircraft applications, a minimum of two grounding jacks shall be required for utility and helicopter aircraft and a minimum of four grounding jacks shall be required for other types of aircraft, in addition to those required for fueling or weapons loading or downloading.

c. Weapon grounds. Grounding jacks shall be installed at locations convenient for use in handling of weapons or other explosive devices.

Compliance shall be verified by test and inspections.

Requirement Rationale (A5.11.1): Grounding between air vehicles and servicing equipment is essential to prevent safety hazards from electrostatic charging effects. The grounding provisions provide paths for equalization of voltage potentials between various points. Grounding jacks must be located at a sufficient number of locations to provide ease of maintenance and to comply with international agreements.

It is well established that sparks due to voltage potential differences between aircraft and servicing equipment can be sufficient to ignite fuel vapors. The motion of fuel during refueling operations is a large contributor to static charging. There is also a concern to prevent electrostatic discharge during ordnance handling. EIDs used in ordnance are potentially susceptible to inadvertent ignition from static discharge.

Electrical resistance between the grounding jack and vehicle structure must be controlled to ensure that an adequate connection is present to dissipate static charge.

Requirement Guidance (A5.11.1): Relatively poor electrical connections (much greater than the specified one ohm) are adequate to dissipate static charge. However, controls must be imposed which indicate that a reasonable metal-to-metal connection is present. Allowing values greater than 1.0 ohm could result in questionable or erratic connections being considered adequate.

Technical Order 00-25-172 provides requirements for grounding of Air Force aircraft during servicing. MIL-HDBK-274 provides information for naval aircraft operations and maintenance personnel to ensure that aircraft are properly and safely electrically grounded for both static and power.

Connection between the aircraft and servicing equipment in the presence of potentially hazardous materials is necessary to prevent potential problems due to electrostatic discharges between servicing equipment hardware and aircraft structure.

International agreements require common interfaces for aircraft static grounding. ISO 46 provides the physical description of grounding jack provisions to ensure interface compatibility. MIL-C-83413 specifies hardware for aircraft static grounding.

Requirement Lessons Learned (A5.11.1): Aircraft fuel fires have been attributed to electrostatic discharge. Precisely demonstrating that an electrostatic discharge caused a mishap is usually not possible due to difficulty in reproducing conditions that were present.

Grounding jacks on aircraft in the field have been found to be electrically open-circuited with respect to the aircraft structure due to corrosion. It is important that corrosion control measures be implemented at the time of installation.

Verification Rationale (A5.11.1): To ensure safety, compliance with provisions for grounding jacks must be verified.

Verification Guidance (A5.11.1): Placement and number of jacks can be verified by test of required distances and inspection. Proper bonding resistance can be verified by test with an ohmmeter.

Verification Lessons Learned (A5.11.1): The availability of grounding jacks on modern aircraft has minimized the probability of an explosion during fueling and ordnance handling.

Proper treatment of surfaces should be reviewed to determine if measures have been implemented to ensure that life cycle issues have been addressed such that corrosion will not degrade electrical bonding of the jacks over time.

A5.11.2 Servicing and maintenance equipment grounds. *Servicing and maintenance equipment shall have a permanently attached grounding wire suitable for connection to earth ground. All servicing equipment that handles or processes flammable fuels, fluids, explosives, oxygen, or other potentially hazardous materials shall have a permanently attached grounding wire for connection to the system. Compliance shall be verified by inspection.*

Requirement Rationale (A5.11.2): Grounding provisions are required to prevent electrical shocks to personnel and potential arcing in the presence of hazardous materials.

Requirement Guidance (A5.11.2): Electrical fault conditions within the servicing and maintenance equipment can cause hazardous voltages to appear on the structure of the equipment. The grounding wire for connection to earth is necessary to allow fault currents to flow and actuate circuit protection devices, thereby removing the hazardous voltage. If an earth ground is always present through the power cord to the equipment, then separate ground provision should not be necessary. The grounding wire for connection to the system prevents voltage differences from developing due to static charging effects, which can cause arcing and potential ignition of flammable vapors. If the servicing connection is designed to provide an electrically conductive path between the system and the servicing equipment, then a separate grounding wire should not be necessary.

Requirement Lessons Learned (A5.11.2): Not applicable

Verification Rationale (A5.11.2): The implementation of grounding needs to be verified.

Verification Guidance (A5.11.2): Inspection of hardware or drawings is adequate to ensure that appropriate grounding provisions are included.

Verification Lessons Learned (A5.11.2): Not applicable.

A5.12 TEMPEST. *National security information shall not be compromised by emanations from classified information processing equipment. Compliance shall be verified by test, analysis, inspections or a combination thereof. (NSTISSAM TEMPEST/1-92 and NACSEM 5112 provide testing methodology for verifying compliance with TEMPEST requirements.)*

Requirement Rationale (A5.12): Compromising emanations are unintentional intelligence bearing signals, which if intercepted and analyzed, would disclose national security information transmitted, received, handled, or otherwise processed by any classified information processing system. The requirement for TEMPEST is found in DoDD 5200.19 (classified). For Air Force aircraft, this requirement is generally applied to the communications subsystem only.

Requirement Guidance (A5.12): Baseline requirements are contained in NSTISSAM TEMPEST/1-92, NSTISSAM TEMPEST/1-93, NSTISSAM TEMPEST/2-95, NACSEM 5112, and MIL-STD-1680 (SH).

The need to apply TEMPEST requirements is determined by the CTTA. The CTTA considers several vulnerability and threat factors to determine the residual risk to which the information is exposed. The CTTA then determines if countermeasures are required to reduce risk to an acceptable level and identifies the most cost effective approach to achieving imposed TEMPEST requirements.

Points of contact for the services are as follows:

Navy: NISE East, PO Box 190022, North Charleston, SC 29419-9022. Telephone: (800)-304-4636.

Air Force: HQ AFCA/SYS, 203 West Losey Room 2040, Scott AFB, IL 62225-5234. Telephone: (618)-256-2828.

Army: Deputy Chief of Staff for Intelligence, ATTN: DAMI, 1000 Army Pentagon, Washington, DC 20310-1000. Telephone: (703)-695-8909.

Requirement Lessons Learned (A5.12): In some cases, the RE102 limits of MIL-STD-461D are considered an acceptable risk level for TEMPEST control of unintentional radiated electromagnetic emissions.

Additional TEMPEST lessons learned fall into three categories: 1) cases where inadequate requirements were levied on the system; 2) cases where requirements were appropriate, but implementation or procedural errors resulted in potentially compromising emissions; and 3) cases where unnecessarily harsh requirements were levied on the system resulting in questionable expenditure of program funds. The former and latter categories have been judged to be equally inappropriate. The second must be considered as cost and risk trades for the program. To address these three issues, National Policy established the CTTAs to ensure a balance of risk and cost through implementation of a risk management process.

Verification Rationale (A5.12): Good EMC design practices can significantly reduce, but not necessarily eliminate, the risk of compromising national security information. Depending upon the environment in which these systems will operate, this risk may be unacceptable. The CTTA should take into account the risk (such as the location, the level being processed, amount being processed, and so forth) and weigh it against the cost prior to accepting TEMPEST compliance by analysis or inspection.

Verification Guidance (A5.12): Test guidelines can be found in the documents referenced in the verification requirement.

Verification Lessons Learned (A5.12): Due to the nature of TEMPEST testing, lessons learned are often classified. While most programs take TEMPEST into account during the design phase, a large number of discrepancies are still found. Strictly using analysis to verify system performance can be inherently risky. When certification tests have been run on systems, the tests have sometimes revealed that a system did not meet the applicable standards. It is important to note that the CTTA may consider the option of analysis or test certification as a trade-off for possible cost savings versus the risk associated with a specific program.

A5.13 Emission control (EMCON). *For Army applications, Navy applications, and other systems applications capable of shipboard operation, unintentional electromagnetic radiated emissions shall not exceed -110 dBm/m*^{2} *at one nautical mile (-105 dBm/m*^{2} *at one kilometer) in any direction from the system over the frequency range of 500 kHz to 40 GHz. Unless otherwise specified by the procuring activity, EMCON shall be activated by a single control function for aircraft. Compliance shall be verified by test and inspection.*

Requirement Rationale (A5.13): Operations on Naval ships are frequently conducted in electromagnetic silence which is the most stringent state of EMCON. Other systems located onboard the ship (such as aircraft, tow tractors, fire control radars, and ship communication systems) are not permitted to transmit on any radios, radars, and navigation equipment over the frequency range of 500 kHz to 40 GHz. This operation has resulted in requiring systems that deploy on ships to be capable of controlling emissions from their onboard active transmitters by quickly changing operating mode to receive, standby, or off and to control all other unintentional emissions such that they are undetectable. The single EMCON control function is necessary to quickly put all the complicated subsystem in the correct non-emitting mode to meet the EMCON level with minimal error by the human operator.

After aircraft have been launched from the ship, EMCON is frequently used to avoid detection of the aircraft.

Army surface systems impose EMCON requirements to minimize detection and provide inter-platform compatibility between one system’s radios and another system’s unintentional emissions.

Requirement Guidance (A5.13): The highest state of EMCON used aboard Naval ships is complete RF silence; however, other states of EMCON exist. Based on the activity of possible threats and operational needs for safety and security, normal active emissions are permitted for selected frequency ranges. For instance, if normal UHF communications is authorized, then it could be called EMCON Alpha. Further states are set depending upon which transmitters (frequency ranges) are authorized to be active. Typically, the systems being developed under this standard will be either all on or all in the EMCON mode with no sub-states. Some subsystems are normally in a non-emitting mode and are not controlled by the EMCON function. A system such as the UHF communications is always in receive unless the operator presses the push-to-talk button. Therefore, it is already in a non-emitting mode, and if EMCON Alpha was authorized, the radio could transmit without deactivating the EMCON function. It is recognized that the single EMCON function does not fit all systems. The procuring activity should tailor this requirement to the system.

It is important to note the need for complete electromagnetic silence from all aspects of the system. Positively no emission in excess of the specified level are permitted from antenna-connected sources or from unintentional sources such as cables and equipment. The electronic protect (EP) requirement (section 5.14) allows transmissions with the intention of denying detection by the use of space, time or energy level.

In an effort to reduce the complexity of developing ground systems for the Army, the EMCON requirement is being used to set levels for unintentional emissions from systems that would interfere with other platform's radio operations. At the same time they are minimizing the vulnerability of exploitation of unintentional emissions such as EMI radiated due to ignition noise and electronic control systems.

Guidance on EMCON can be found in NAWCWPNS TS 92-78.

Requirement Lessons Learned (A5.13): Radio silence, now called EMCON, was used very effectively during World War II to hide the location of Naval ships from the Japanese. EMCON was used by Naval forces in the Viet Nam and Korean War to deploy aircraft over the forward edge of the battle area. These tactics continue today in modern Naval forces.

The single EMCON button has significantly reduced operator workload on systems where it could be supported. The single EMCON button is only practical on a tightly integrated system such as an aircraft. However, care must be exercised to ensure that the control circuit to the transmitter is maintained as functional and means are provided for the operator to know of a malfunction.

Local oscillator emissions must be controlled for a system to meet EMCON requirements.

Verification Rationale (A5.13): Almost all systems have a variety of apertures that are sources of unintentional radiation. Since many of these apertures are inadvertent, it is only possible to find some emissions by test. Analysis is not reliable.

Verification Guidance (A5.13): The measurement of the EMCON level is normally conducted in a anechoic chamber at a distance close to the system where normal laboratory equipment can be used to detect the emissions. After several years of EMCON tests by the Naval Air community, the distance commonly used is 10 meters from the system. At this distance the values measured are related to the EMCON limit through the inverse square law of EM propagation. The following equation is used:

$$P_d = \frac{P_t G_t}{4\pi r^2}$$

where:

P_d = Power density (watts/meter^2)
P_t = Power transmitted (watts)
G_t = Gain of transmitting antenna
r = Radius from aircraft (meters)

Since the power density is proportional to $1/r^2$ with other parameters remaining constant, the limit at 10 meters, assuming far-field conditions are maintained, is calculated by:

Limit = -110 dBm/m^2 + 20 log (1852 meters per nautical mile/10 meters) = -64.6 dBm/m^2.

EMCON measurements are made at 4 positions around the system, usually at 45, 135, 225 and 315 degrees from the front. Additional positions are added above, below and around the system based on antennas positions and apertures. The measurement equipment used to detect the emission is a spectrum analyzer augmented with a preamplifier or a EMI receiver with a noise figure capable of having 6 dB or more margin between the noise floor and the derived EMCOM limit. Typical band widths used are 1 kHz for 500 kHz to 1 MHz, 10 kHz for 1 MHz to 30 MHz, 30 kHz for 30 to 1 GHz and 100 kHz for 1 GHz to 18 GHz. No distinction is made between narrow or broadband signals. At each position, an ambient measurement is made with all equipment on the system turned off, followed immediately by a system EMCON measurement. The two measurements are compared to remove emissions common to both. Emissions that remain in the emission measurement are evaluated if they exceed the derived EMCON level. Those emissions that exceed the level undergo further testing and analysis to determine compliance. Issues such as near-field effects and ground reflections need to be considered. On mature systems which are having additional capability added, the ambient measurement can be used to measure the system's active emissions, and the EMCON measurement then detects the new capability in the EMCON mode. Pre-existing emissions from the mature system are removed from evaluation.

The developing activity can show by analysis of extrapolated measurements that the system does not radiate above the EMCON limit. The extrapolated MIL-STD-461D limit (for Navy and Air Force external aircraft and space systems applications) is less than the EMCON limit at all frequencies. For example, the maximum RE102 value of 69 dBμV/m occurs at 18 GHz and is 2 dB below the EMCON limit. Extrapolating 69 dBμV/m to 1 nautical mile (1852 meters), assuming far-field conditions and using the relationship that $P_d = E^2/377$ (where P_d is power density and E is field strength), yields:

$$69 \text{ dB}\mu\text{v/m} - 116 \text{ (dBm/ m}^2)/(\mu\text{V/m}) - 20 \log \text{ (1852 meters/1 meter)} = -112 \text{ dBm/m}^2$$

Verification Lessons Learned (A5.13): For equipment which is required to meet the radiated emission limits of MIL-STD-461, there is assurance that the overall system will comply with the EMCON requirement for any emission contributions from this equipment at most frequencies of interest. When other EMI standards are imposed, analysis is necessary to determine whether the requirements are adequate for EMCON at the system-level.

Naval ship subsystems typically have a standby select switch for powering up the subsystems without deliberately transmitting.

A5.14 Electronic protection (EP). *For Army aircraft and Navy aircraft applications, intentional and unintentional electromagnetic radiated emissions in excess of the EMCON limits shall preclude the classification and identification of the system such that system operational performance requirements are met. Unless otherwise specified by the procuring activity, EP shall be activated by a single control function. Compliance shall be verified by test, analysis, inspections, or a combination thereof.*

Requirement Rationale (A5.14): It is not always possible to maintain EMCON. Safety and tactical needs require the radiation of signals from antennas. However, at normal levels and modes these signals can compromise the system. The EP level permits the emission because either the signal level or signal characteristics have been controlled to deny exploitation by threat forces. A single control function is used to integrate an entire suite of emitters on a system to meet the requirement.

Requirement Guidance (A5.14): EP is a new term. In the past the term used was electronic counter counter-measures (ECCM). The two areas grouped under EP or ECCM are anti-jam and low probability of intercept. This requirement is derived from low probability of intercept concerns. Active emission control became a logical extension of EMCON in the passive or non-active mode at the system-level. Further evolution of the area concluded that active emission control is properly called EP.

There are three possible ways to comply with the requirement. First is the use of space and time to deny detection of the signal. When space is used, the signal level at a detection point of 1 nautical mile or 1 km should meet the EMCON limits. Detection can be controlled by power level of the transmitter, space positioning of the emitted signal, pulse coincidence, and frequency coincidence. The second way is to preclude classification of the signal being emitted by the system. A signal's fingerprint can be modified to be other than the norm, making it difficult to decide who, what, or why the signal is being emitted. The third way is to preclude identification of the signal. The detector of the emission is denied displaying of the information, or the response to the emission is denied (such as missile response and network alert).

Requirement Lessons Learned (A5.14): Not applicable.

Verification Rationale (A5.14): The EP subsystems must be verified to ensure there are no emissions which would could be exploited by a threat to the system. The verification must be accomplished under various types of methods because of the numerous ways available to control and deny access to the emissions.

Verification Guidance (A5.14): Testing for EP can be performed at the bench level (spectrum signature and identification tests), during system tests (system integration and secure testing), and during operation tests (for example, flight tests for space coincidence, classification, and identification testing).

Verification Lessons Learned (A5.14): Past efforts have concentrated on single subsystem EP. Integration of the various subsystems at the system will lead to a more capable system that is less vulnerable.

Operational testing of EP modes is very restrictive and costly. Maximum effort should be made during bench and system laboratory testing to minimize the operational testing.

CONCLUDING MATERIAL

Custodians:
Navy - AS
Army - SY

Review Activities:
Air Force - 13, 17, 19, 22, 84
Army - AC, AL, AM, AR, AT, AV, CE, CR, GL, MD, MI, PT, SC, TE
Navy - CG, EC, MC, OS, SH, YD
JSC
DSWA

Preparing Activity:
Air Force - 11

(Project EMCS - 0154)

STANDARDIZATION DOCUMENT IMPROVEMENT PROPOSAL

INSTRUCTIONS

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I RECOMMEND A CHANGE:	1. DOCUMENT NUMBER **MIL-STD-464**	2. DOCUMENT DATE (YYMMDD) 970318

3. DOCUMENT TITLE

Electromagnetic Environmental Effects, Requirements for Systems

4. NATURE OF CHANGE (Identify paragraph number and include proposed rewrite, if possible. Attach extra sheets as needed.)

5. REASON FOR RECOMMENDATION

6. SUBMITTER

a. NAME (Last, First, Middle Initial)	b. ORGANIZATION	
c. ADDRESS (Include Zip Code)	d. TELEPHONE (Include Area Code) (1) Commercial (2) AUTOVON *(If applicable)*	7. DATE SUBMITTED *(YYMMDD)*

8. PREPARING ACTIVITY

A. NAME ASC/ENSI Bldg 560	B. TELEPHONE (Include Area Code) (1) Commercial (937) 255-6295 (2) AUTOVON (If applicable) 785-6295
C. ADDRESS (Include Zip Code) 2530 Loop Road - West Wright-Patterson AFB OH 45433-7101	IF YOU DO NOT RECEIVE A REPLY WITHIN 45 DAYS, CONTACT: Defense Quality and Standardization Office 5203 Leesburg Pike, Suite 1403, Falls Church VA 22041-3466 Telephone (703) 756-2340 AUTOVON 289-2340