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SY80-2-93

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ELECTROMAGNETIC TRANSIENT TEST REDUCTION INVESTIGATION

1 AUGUST 1993

PREPARED BY

**NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND 20670-5304
CODE SY84**

PREPARED FOR

**NAVAL AIR SYSTEMS COMMAND
AIR-51641C
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This study documents a systematic research effort to determine the feasibility of reducing Naval aircraft transient test requirements. Electromagnetic transient testing environments and test requirements were reviewed and compared to determine if potential overlap exists. Possible overlaps in environments, requirements, test methodology, test equipment, and waveform parametric characteristics were evaluated. The study shows that direct comparisons between lightning, EMP, and ESD can be evaluated by using norms. However, other factors such as instrumentation and the environment simulation method prevent true test integration. One technique has potential to reduce aircraft transient testing using current injection. The technique involves using test data to develop bounding direct-drive waveforms across multiple transient environments.

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Approved for
Release By

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Mr. John Dawson
Naval Air Warfare Center Aircraft Division
Patuxent River, Maryland
Code SY80, 1 August 1993

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LIST OF ACRONYMS

AR	Autoregression
BURST	Bursted CW Susceptibility Source
CDS	Critically-Damped Sine
CE	Conducted Emissions
CS	Conducted Susceptibility
CW	Continuous Wave
DS	Damped Sine
DSC	Damped-Sine Characterization
E^3	Electromagetic Environmental Effects
EED	Electro-Explosive Device
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EMCS	Electromagnetic Compatibility Standardization
EMCON	Emission Control
EMI	Electromagnetic Interference
EMP	Electromagnetic Pulse
EMV	Electromagnetic Vulnerability
ESD	Electrostatic Discharge
FAANTAEL	Fleet Aircraft Assessment for Navy Testing and Analysis for EMP Limitations
HEMP	High Altitude EMP
HERF	Hazardous Electromagnetic Radiation to Fuel
HERO	Hazardous Electromagnetic Radiation to Ordnance
HERP	Hazardous Electromagnetic Radiation to Personnel
HIRF	High Intensity Radiated Fields

LIST OF ACRONYMS (CONT'D)

HPD	Horizontally Polarized Dipole
HPM	High Power Microwave
kHz	Kilohertz
kV	Kilovolt
LLCW	Low-Level Continuous Wave
MHz	Megahertz
MIL-STD	Military Standard
MOD	Modulated Susceptibility Source
NAVAIR	Naval Air Systems Command
P-Static	Preciptiation Static
RADHAZ	Radiation Hazards
RE	Radiated Emissions
RS	Radiated Susceptibility
SPAWAR	Space and Naval Warfare Systems Command
TRANS	Transient Type Phenomena
VPD	Vertially Polarized Dipole

1. INTRODUCTION

1.1 BACKGROUND

Naval aircraft electromagnetic environmental effects (E^3) testing evaluates the aircraft's capability to operate in all electromagnetic (EM) environments. As illustrated by Figure 1, many elements contribute to the E^3 problem. Over the years, the need to protect against the effects of these problems upon aircraft has generated various environment specifications, test requirements, and test capabilities.

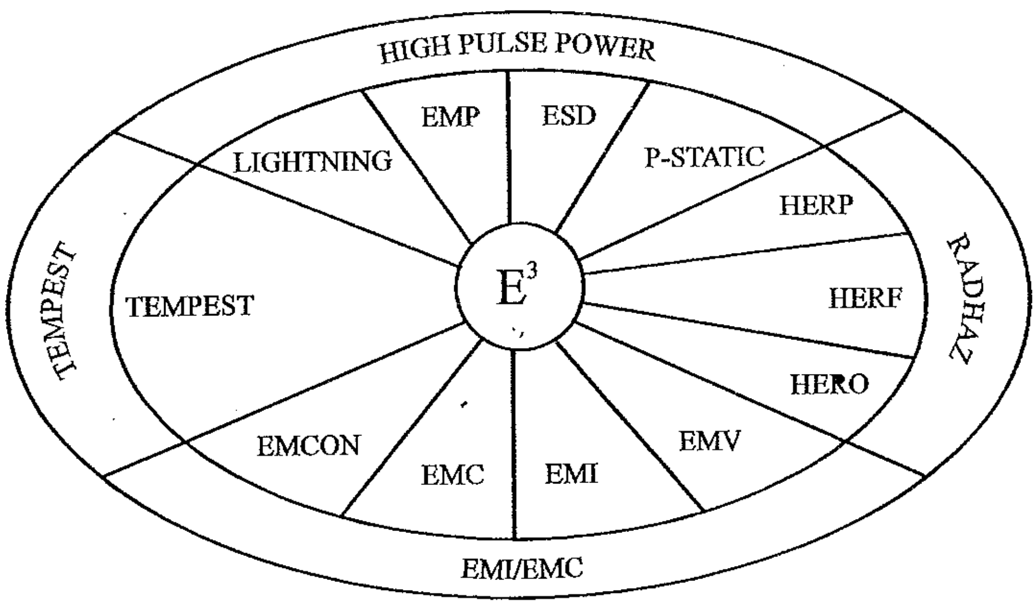

Figure 1. The Elements of E^3

Naval aircraft are evaluated by exposing the aircraft or subsystem (boxes) to radiated or conducted simulations of the environment or by testing boxes to specified requirements. The continuing emphasis on cost-effective testing has repeatedly challenged the Navy to develop means to test more efficiently. Although E^3 testing includes several elements, this study focused on EM transients. The study effort was funded and directed by the NAVAIR Fleet Aircraft Assessment for Navy Testing and Analysis for EMP Limitations (FAANTAEL) Program.

1.2 PURPOSE

This study was designed to identify any overlaps in EM transient characteristics or test requirements which could be eliminated to reduce EM transient testing. A secondary purpose was to create a framework for similar investigations of all electromagnetic environments. The goal is to improve the naval aircraft test and evaluation efforts and reduce overall E^3 test costs.

1.3 SCOPE

The study was confined to naval aircraft E^3 testing. Figure 2 shows the inter-related factors considered during testing. The environmental and test requirement factors shown in Figure 2 were initially addressed across all elements of E^3 plus High Power Microwave (HPM) effects. The Hazardous Electromagnetic Radiation to Personnel (HERP) element of E^3 was excluded. Both system-level and box-level effects were addressed for the environment and requirement factors, and condensed to a subset representing Electromagnetic Pulse (EMP), Electrostatic Discharge (ESD), and lightning.

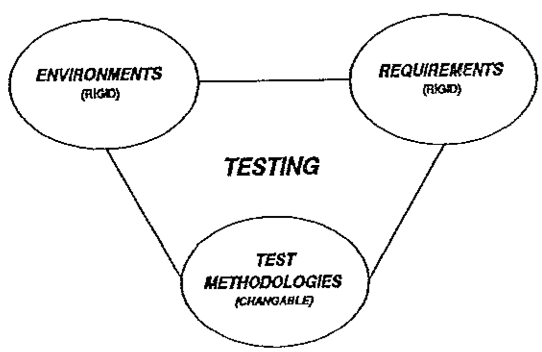

Figure 2. Inter-related Factors of Testing

1.4 TECHNICAL APPROACH

The study began with a review of all specified EM environments and EM test requirement documents for naval aircraft. These specifications and requirement documents were identified by reviewing MIL-HDBK-237A [Ref 1] and the Draft Electromagnetic Compatibility Standardization (EMCS) Program Plan [Ref 2]. A matrix approach was used to visually summarize the environments and requirements information. Each matrix listed the E^3 elements on one side of the matrix and the type of effects that are observed on aircraft across the top of the matrix. The matrix structure produces groupings which can be used to identify which environments and requirements should be compared for possible overlaps. One such grouping is EM transients for both systems and boxes. The remainder of the study focused on the EM transients.

The study followed the six basic steps shown in Figure 3. Based on conclusions from these steps, the approaches or techniques that offered the best feasibility for ultimately reducing the number of tests required were identified. The study steps were:

Step 1: Environmental Effects Reduction--All EM environments were evaluated by considering specific types of effects, e.g., conducted emissions (CE). A matrix approach for both systems and boxes was used to identify natural groupings of environmental effects. Subsequently, reduced matrices were derived based on groupings for similar transient environments (Appendix A).

Step 2: Requirements--All Navy aircraft E^3 requirements documents were similarly evaluated and reduced for transient-type testing. Part of this review involved a search for any related study documents including prior test reduction studies (Appendix B).

Step 3: Transient Characteristics--Each identified transient test requirement was evaluated in terms of how it's waveform is specified for generation during testing (Appendix C).

Step 4: Test Configurations--This section further evaluated the specific naval aircraft methods used for each transient test. The objective was to compare test requirements and set-up configurations for transient-type tests on an equal basis (Appendix D). Finally, based on this comparison, a configuration matrix was developed.

Step 5: Parametric Characteristics--In this step, each EM transient test waveform was evaluated in terms of its characteristics (Appendix E). Waveform comparisons using norm information were presented. In addition, techniques to create realistic bounded composite test waveforms were discussed.

Step 6: Conclusions and Recommendations--The approaches determined most feasible to improve transient testing were identified in this step.

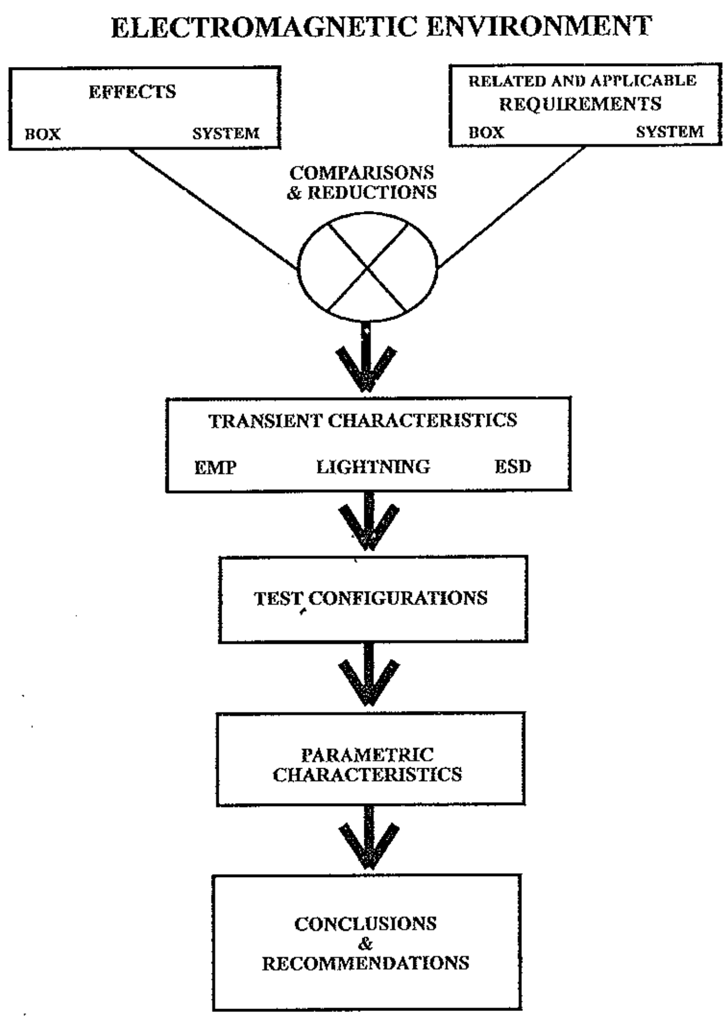

Figure 3. Study Flow Diagram

2. RESULTS AND DISCUSSION

2.1 ENVIRONMENTAL EFFECTS REDUCTION

The first step in the study reviewed all EM environments. Two matrices were developed from information obtained through the review - one for system-level effects and one for box-level effects. An example for the box-level effects is shown in Table 1. EMC and EMI environments were combined for convenience.

The initial matrices were reduced depending on the various criteria applied and which common subset of effects (i.e., pulse, CW, transient) was under investigation. The details of the reduction process are given in Appendix A. Reductions indicate which environments could have potential test overlap at either the system or box level. The term "effects" was broadly used since environmental effects on an aircraft can be direct, indirect, or a combination of both.

The final matrix reductions for aircraft transient environments at the box and system levels are shown in Tables 2 and 3. Each reduced matrix indicates which EM elements should be compared for similarities and subsequent test reductions.

2.2 REQUIREMENTS

Following the environment groupings, naval aircraft EM requirements documents were similarly reduced. This review, included in Appendix B, reduced transient phenomena based on similar test methods. The P-Static test for receiver noise and the lightning-related corona test, for example, were eliminated due to their unique test methods and requirements.

Table 1. Box-Level Effects Comparison Matrix

ENVIRONMENT	EFFECT							
	CE	RE	CS	RS	MOD	CW	BURST	TRANS
TEMPEST	X	X			X			
EMC/EMI	X	X	X	X	X	X		X
EMV*			P	X	X	X	X	
RADHAZ		X						
HERO			P	X	X	X	X	
HERF			X	X			X	
EMCON		X			X	X	X	
HPM				X	X	X	X	
EMP			X	X				X
ESD			X					X
P-STATIC**								X
LIGHTNING***			X					X

*	Indicates environment defined many ways and changes periodically when new radars or communications systems are developed. Uses RS03 test methods.
**	P-Static is a system environmental effect which can impact box level operation.
***	Although Corona is similar to P-Static, it is included with lightning only because it is incorporated within a lightning requirements specification. P-static is much higher in frequency than Corona.
P	Indicates effect could be tested in this manner but currently not used. The technique would involve a re-injection of a previously measured system level threat. The current technique used will be discussed later in this paper.
CE	Conducted Emission
RE	Radiated Emission
CS	Conducted Susceptibility
RS	Radiated Susceptibility
MOD	Modulated Susceptibility Source
CW	Continuous Wave Susceptibility Source
BURST	Bursted CW Susceptibility Source
TRANS	Transient-Type Phenomena

Table 2. Box-Level Reduced Effects Comparison Matrix

ENVIRONMENT	EFFECTS					
	CS	RS	MOD	CW	BURST	TRANS
EMP/ESD/LIGHTNING	X					X
EMP*		X				X

*although the environment is radiated and referenced to an EMC/EMI document, at the box level some testing is conducted

Table 3. System-Level Reduced Effects Comparison Matrix

ENVIRONMENT	EFFECTS					
	CS	RS	MOD	CW	BURST	TRANS
ESD/P-STATIC/LIGHTNING	X					X
EMP/LIGHTNING*		X				X

*although the environmental threat for indirect effects is radiated, the test for this environment is conducted

A search for related non-Navy documents, including prior test reduction studies, was undertaken during the document review. Some documents are referenced, but not directly evaluated herein. Only one previous study was identified. The study compared lightning, EMP, and High Intensity Radiated Fields (HIRF) [Ref 3] effects. The report was considered in this study but did not affect the results.

Table 4 lists the requirement documents subsequently evaluated, and the final reduced set of transient test requirements is shown in Table 5.

Table 4. Requirements Documents

REQUIRED DOCUMENTS	
MIL-STD-331B	Fuze and Fuze Components, Environmental and Performance Tests for (preliminary ESD document)
MIL-STD-449	Radio Frequency Spectrum Characteristics, Measurement of
MIL-STD-461C*	Electromagnetic Interference Characteristics, Requirements for Equipment
MIL-STD-469A	Radar Engineering Design Requirements, Electromagnetic Compatibility
MIL-STD-1385B	Preclusion of Ordnance Hazards in Electromagnetic Fields, General Requirements for (HERO test document)
MIL-STD-1757A	Lightning Qualification Test Techniques for Aerospace Vehicles and Hardware
MIL-B-5087B	Bonding, Electrical, and Lightning Protection, for Aerospace Systems (B for bonding and P-static, A for corona)
MIL-E-6051D	Electromagnetic Compatibility Requirements, Systems
MIL-D-0129D	Dischargers, Electrostatic, General Specification for
MIL-STD-1795A	Lightning Protection of Aerospace Vehicles and Hardware
DOD-STD-2169	High Altitude Electromagnetic Pulse (HEMP) Environment (this is the primary HEMP test document)
MIL-HDBK-235-1	Electromagnetic Radiated Environment Considerations for Design and Procurement of Electrical and Electronic Equipment (235-2A primary E^3 test environment document)

* MIL-STD-462 is not listed since it only supports MIL-STD-461 with test setup information

Table 5. Summary of Required Documents for Aircraft Transient Testing

SPECIFICATION	METHOD	TEST	WAVEFORM
MIL-STD-1757A Lightning	CS	T02 Direct Eff. Struct. T03 Direct Eff. Vapor T05 Indirect (primary)	Waveform A Waveform A Waveform E
MIL-STD-331B ESD	CS	F1 Electrostatic Disc.	Human Body 25 KV Waveform Air Rep. 300 KV Waveform
MIL-STD-461C EMP	RS	RS 05	Double Exp. Waveform

CS Conducted Susceptibility
RS Radiated Susceptibility

2.3 INITIAL MATRIX SUMMARY

An important similarity emerged from the initial matrix reductions. Transient testing could have potential overlap at either the box or system level. However, some environments are manifested differently at each level. EMP, for example, appears strictly as a radiated field to the aircraft platform. At the box level, EMP appears as a conducted current pulse through the aircraft cabling or as a radiated field through an aperture, such as a cockpit window.

MIL-STD-461C [Ref 4] EMP tests are applicable at the box level except for RS05, which can be applied at the box or system level. MIL-STD-331B [Ref 5] relates to ESD testing of certain equipment types at any level. This led to the conclusion that although an eventual reduction could take place at the box or system level, the environments can only be compared once they appear in the same form. Therefore, the evaluation highlighted the need to further reduce specific tests into similar parameters for direct comparisons.

It is also apparent that each EM transient element has developed, over the years, specific test techniques and requirements tailored by experience, simulation operational needs, and measurement capabilities. A basic review emphasizing present test and measurement capabilities and a more integrated approach not constrained by official requirement documents and specifications may identify several test overlaps and reductions. However, this type of investigation was outside the scope of this study.

2.4 DESCRIPTION OF TRANSIENT TESTING

Each of the transient test waveforms and test parameters are described in detail in Appendix C. An overview of each test from Table 5 is presented below.

2.4.1 Lightning

Aircraft lightning tests use waveforms that create responses intended to be easily extrapolated to the ideal. The specified waveform in MIL-STD-1795A [Ref 6] (Figure 4) is theoretically ideal. The actual waveform used for testing does not need to duplicate the ideal, only one or more of the waveform's primary electrical parameters. Qualification test waveforms are specified in MIL-STD-1757A [Ref 7]. There are both voltage and current waveforms specified (Appendix C). Also, there is one additional current waveform used for indirect effects testing (Waveform E). At present, current waveforms A and E are used for Navy aircraft testing. These waveforms formed the basis for comparing lightning, EMP, and ESD characteristics. Figure 5 is the current waveform (A) used for direct effects testing. Figure 6 is the current waveform (E) used to evaluate indirect effects.

2.4.2 Electrostatic Discharge

This requirement is applicable to equipment containing electro-explosive devices (EED's), also referred to as fuses. At present, there are four tests identified in section F of MIL-STD-331B, Electromagnetic and Magnetic Influences. Of these, only subsection F1, ESD, has specific test requirements called out. These are non-instrumented, pass/fail type tests. The other tests are noted as "in preparation" and relate to EMP, EMR, and Lightning.

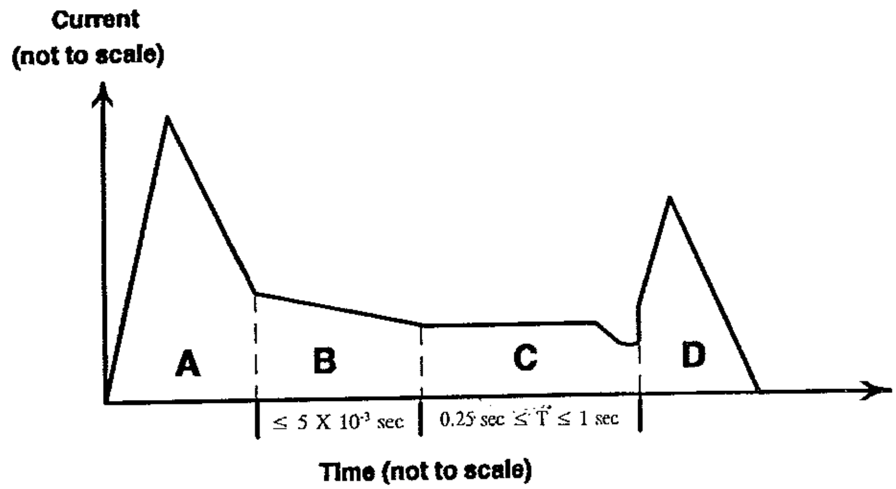

Figure 4. Components of the Theoretical Lightning Current Waveform (MIL-STD-1795A)

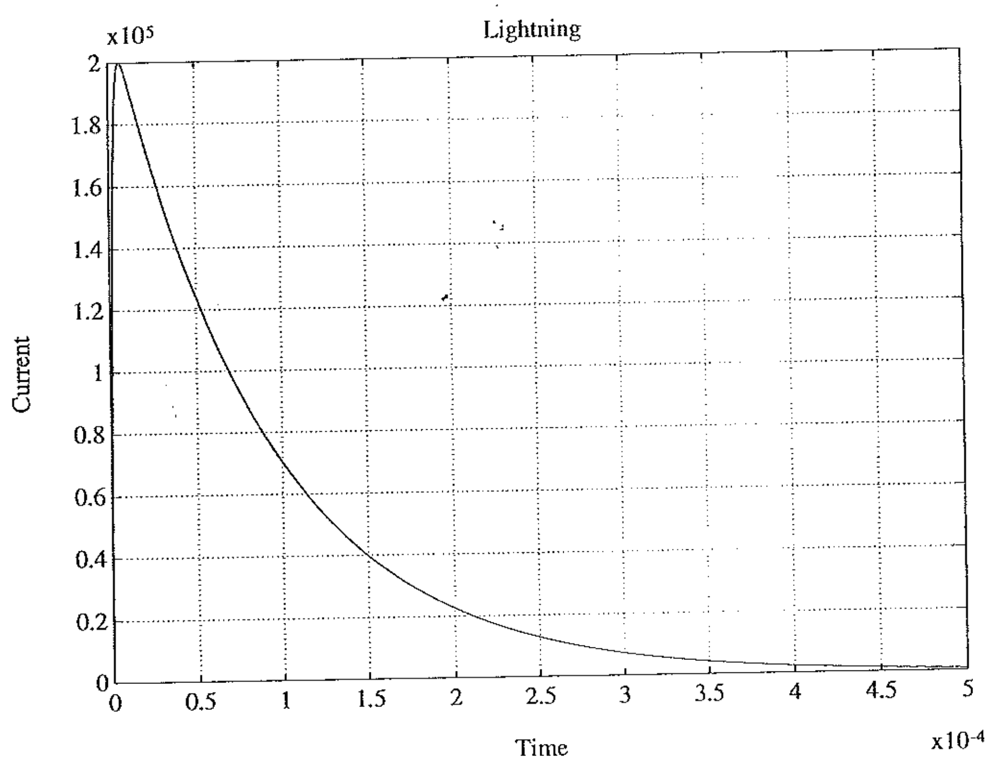

Figure 5. Lightning Current Waveform A (MIL-STD-1757A)

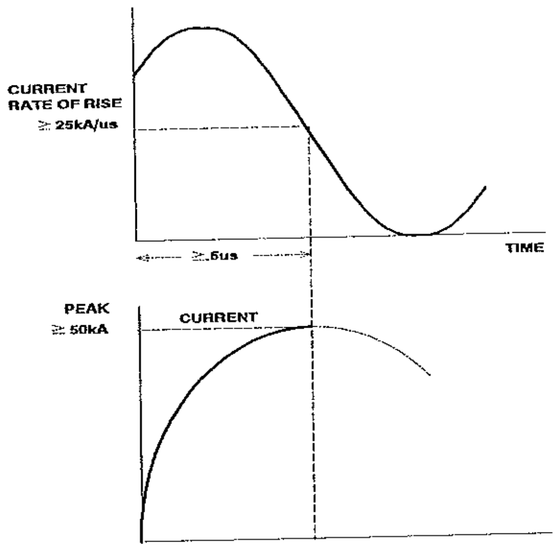

Figure 6. Lightning Current Waveform E (MIL-STD-1757A)

Transient ESD testing is divided into two parts, human-body discharge and air-replenishment discharge. Figure 7 represents the upper and lower bounds on the human-body discharge waveform developed using a capacitor and 500 ohm series resistor. This waveform is characterized by a rise time of 15 nanoseconds (10% to 90% peak value) and a fall time of 150 nanoseconds.

Air-replenishment discharge relates to helicopters and other hovering aircraft that become electrostatically charged by ion emissions from the engines or by triboelectric charge separation on airfoils. Figure 8 represents the air-replenishment waveform developed using a capacitor and 5000 ohm series resistor.

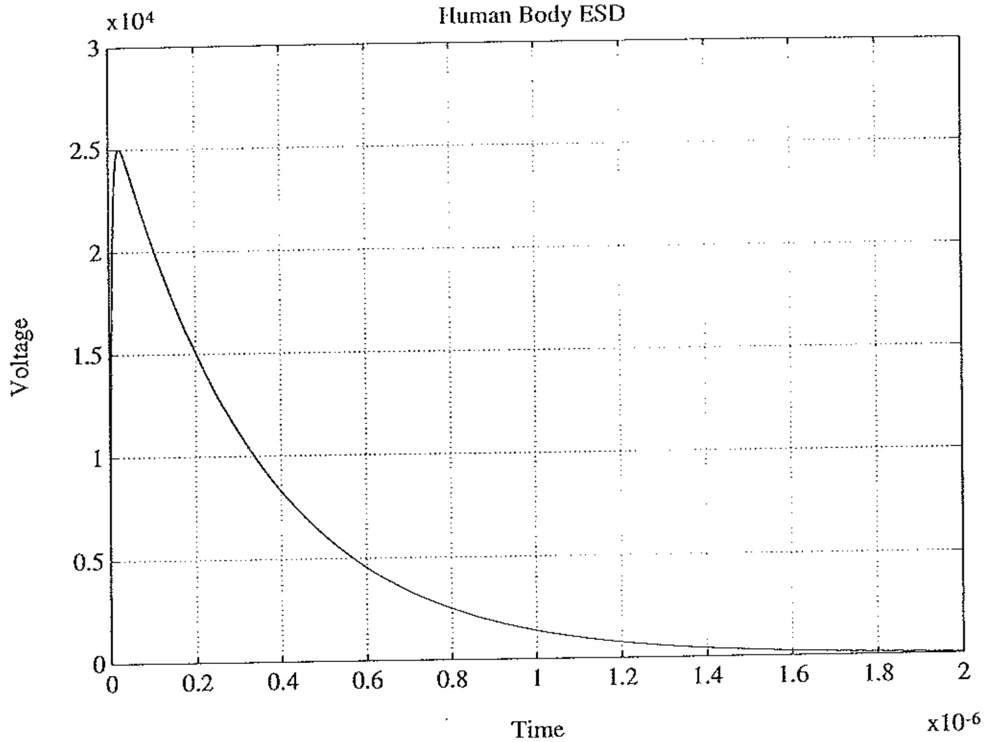

Figure 7. Human-Body Discharge (MIL-STD-331B)

2.4.3 Radiated EMP Transients Testing

Radiated susceptibility RS05 testing is applied to a box or system at the approximate level of the specified environment. Typically, Navy aircraft testing involves two aircraft orientations at each of two simulators. The orientations are with the aircraft nose-on and wing-on at the Vertically Polarized Dipole facility and the aircraft fuselage parallel and perpendicular to the pulser antenna at the Horizontally Polarized Dipole facility. This provides two sets of measurements for vertically polarized EM fields and two sets for horizontally polarized EM fields.

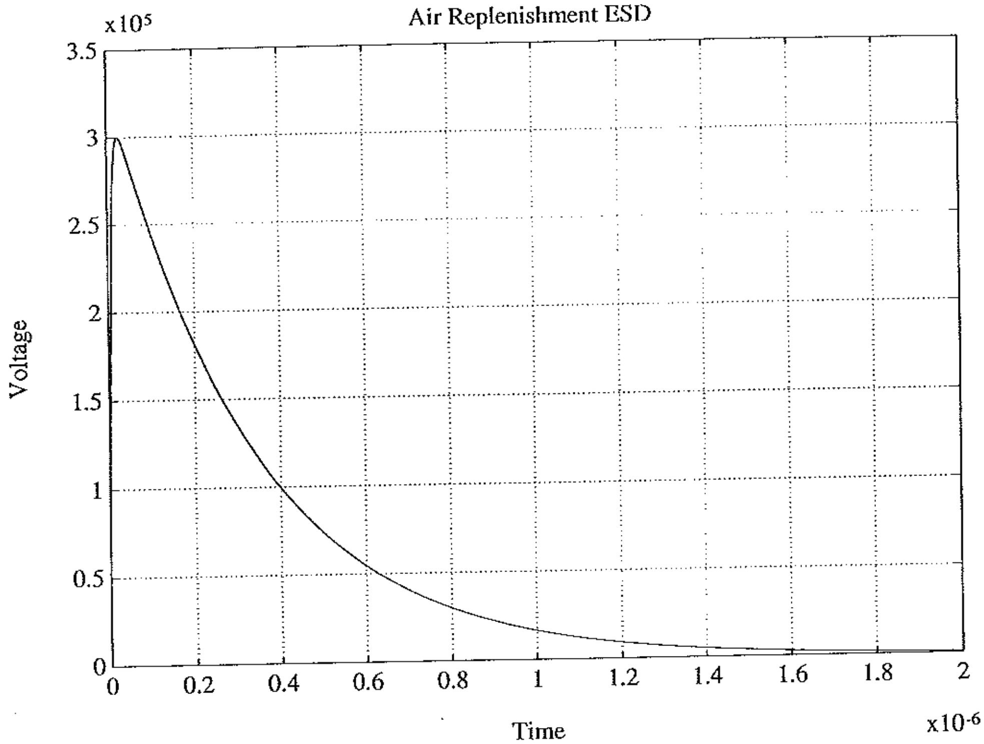

Figure 8. Air Replenishment ESD Waveform (MIL-STD-331B)

The radiating source uses a double-exponential waveform specified by either MIL-STD-462 [Ref 8] or by DOD-STD-2169 [Ref 9]. This study addressed the time-domain MIL-STD waveform only. The MIL-STD-462 (Bell Labs) time-domain waveform is shown in Figure 9.

2.5 TEST CONFIGURATIONS

The evaluation of specific test requirements and methods of performing tests was insufficient by itself to make recommendations for test reductions. A test configuration comparison was needed to identify other potential reduction scenarios. Its development (Appendix D) involved reviewing characteristics, instrumentation, test application conditions and other configuration aspects for each subtest. The objective was to compare physical test requirements and set-up configurations for transient-type tests on an equal basis if possible.

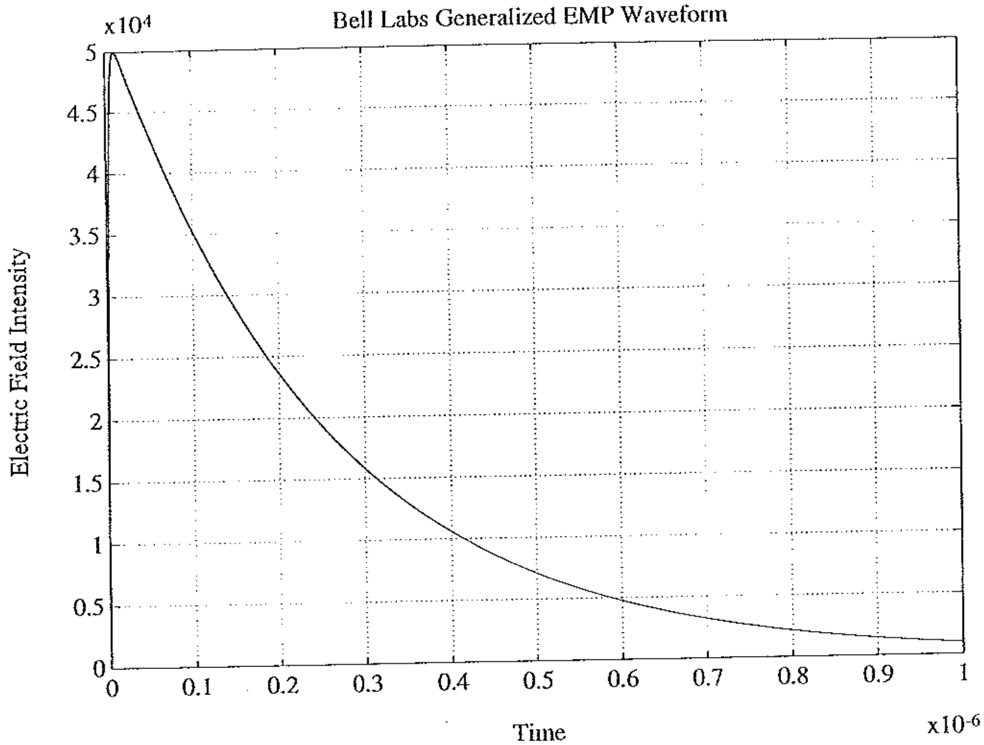

Figure 9. EMP RS05 Radiated Waveform (MIL-STD-461C/462)

The configuration comparison is presented in Table 6. Notice that natural test reduction groupings are not obvious except as related to specific environments. The groupings that appear possible are the various EMP tests and the lightning T02, T03, and T05 test.

Another possibility was the combination of both ESD tests and the lightning T05 test. In this case, ESD tests are not instrumented. A modification of present test methodology and pass/fail criteria would be necessary if the ESD tests were combined with an instrumented test. The configuration comparison indicates it is difficult to identify any eventual test reduction at the system level. This result again emphasized the need for parametric comparisons.

Table 6. Reduced Test Configurations

Test	Vehicle Position or Test Type	Method	Waveform Used	Instrumented for Box Level Re-Injection	Extrapolation Difficulty	Significant Frequency	Test Reduction Potential
*EMP RS05 - HPD	Parallel to Antenna	RS	Double Exponential	Yes	No	10 kHz - 300 MHz	Direct Drive Box Level
*EMP RS05 - HPD	Perpendicular to Antenna	RS	Double Exponential	Yes	No	10 kHz - 300 MHz	Direct Drive Box Level
*EMP RS05 - VPD	Nose On	RS	Double Exponential	Yes	No	10 kHz - 300 MHz	Direct Drive Box Level
*EMP RS05 - VPD	Wing On	RS	Double Exponential	Yes	No	10 kHz - 300 MHz	Direct Drive Box Level
Lightning - T02	Direct Effects	CS	Critically Damped Sine Waveform A	Yes	No**	0 - 20 MHz	Direct Drive Box Level
Lightning - T03	Vapor Ignition	CS	CDS or DS Waveform A	Camera	No	0 - 20 MHz	No
Lightning - T05	Indirect Effects	CS	DS Waveform E	Yes	No	0 - 50 MHz	Can Be Combined With T02
ESD - Human Body	Direct Fuse Injection	CS	CDS	No***	Pass/Fail	10 kHz - 100 MHz	Would Require New Test Method
ESD - Air Replenishment	Direct Fuse Injection	CS	CDS	No***	Pass/Fail	10 kHz - 100 MHz	Would Require New Test Method

* Test is first performed on an un-instrumented powered aircraft to identify anomalies. The aircraft is then instrumented and unpowered to measure induced transients.

** Depends on waveform used. Low level continuous wave (LLCW) involves significant data extrapolation risk. Damped sine (DS) involves some extrapolation risk. Critically-damped sine (CDS) involves very little data extrapolation risk.

*** Testing is un-instrumented with a pass/fail indication.

2.6 PARAMETRIC CHARACTERISTICS

For a closer comparison between E^3 tests, the use of more sophisticated tools such as parametric attributes and elaborate comparison techniques was necessary. Each test waveform can be described by norms and mathematically manipulated to identify waveform similarities and feasible test reductions. A complete description of norms and waveform bounding is provided in Appendix E.

2.6.1 Waveform Parameters

As noted in Appendix E, salient features of complicated waveforms are expressible in scaler quantities called norms. Norms help analyze the way attributes or components of the waveform will interact with systems or devices. Although all transient environment waveforms are comparable in terms of norms, such a comparison at the system level using requirement values would be of little use. However, at the box level, the norms of measured waveforms resulting from any environmental exposure can provide directly comparable parameters.

Carl Baum [Ref 10] was the first to propose the use of norms for EMP transient analysis in 1983. Although there are five common norm attributes (Table 7), only the peak absolute amplitude of a current pulse is used to develop the transient used in current direct-drive testing. Table 7 lists some norms for both radiated RS05 and conducted CS10 testing.

Norms from Table 7 are based on specification documents, not measured data, and are difficult to compare for test overlap directly. In actual Navy aircraft testing, MIL-STD EMP radiated tests use the theoretical waveform. However, conducted box-level tests are based on actual waveforms measured on an aircraft. The norms from these measured waveforms appear to be the proper level for direct comparisons between various transient environments.

Table 7. Waveform Breakdown of Relevant EMP Parameters

PARAMETER	SOURCE	VALUE
$E_o(t)$	Radiated	5.25 x 10^4 v/m
$\alpha\ (s^{-1})$	Radiated	4.0 x 10^6/sec
$\beta\ (s^{-1})$	Radiated	4.8 x 10^8/sec
$I_o(t)$	Conducted	10 amps
i_{peak}	Conducted	10.25 amps

Transient induced characteristics from ESD testing, EMP, and lightning testing are similar at the box level. However, ESD testing, for example, has no measurements associated with it. Therefore, while an overlap in waveform characteristics, in frequency, or in time might indicate the possibility for test reduction, the test methods used place constraints on how a reduction might be applied.

The study did not reveal a solid basis for direct comparisons between environments when any one norm is used, e.g., peak absolute amplitude which is presently used for conducted box-level testing (direct-drive testing). However, the peak absolute amplitude norm which comes from one of four measurements taken at a test point, coupled with the other measured data at the box-level test point, may allow for a feasible composite waveform approach which provides a bounding direct-drive waveform. A further bounding approach combining measured waveforms from both lightning and EMP tests may ultimately lead to a means of combining all EM transient testing.

2.6.2 Bounding Composite Waveforms

The traditional approach used for aircraft EMP and lightning direct-drive testing does not use all of the measured waveforms acquired during testing. The re-injection waveform, although acceptable, does not represent the stimulation characteristics of all of the environmental effects. However, recent research [Ref 11] has determined that a voltage integral waveform developed from the open-circuit voltage waveform and the direct-drive waveform could be integrated numerically to produce an acceptable waveform for re-injection. Therefore, a solution using this approach appeared to be feasible.

Depending on antenna orientation and test configuration, each EMP test point has several current waveform measurement records. One possibility for developing a more accurate re-injection waveform based on any number of sensor measurements would be to combine these measurements and use the waveform norms to evaluate the combined waveform [Ref 12]. The approach involves combining multiple transient response data at each point into a single composite stress waveform test point. The new waveform, termed the "Stress Envelope," would replace the current approach for inductively coupled direct-drive testing. The basic technique of developing a "Stress Envelope" is shown in Figure 10.

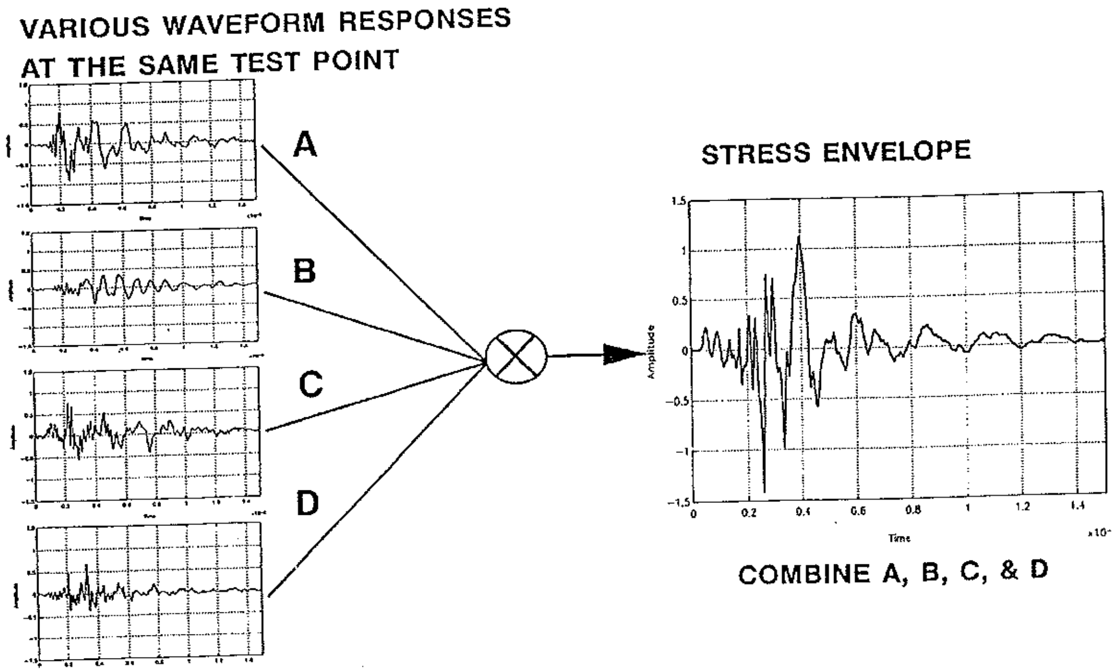

Figure 10. Composite Waveform Development

2.6.3 Methods for Developing Envelopes

Although a number of methods are available for developing envelopes, AR and DSC have been considered in Navy EMP work. AR is a formal mathematical approach which progressively fits each measured test waveform into a single polynomial equation. Damped-sine characterization decomposes a waveform into multiple poles. The resulting poles from all data are then placed in a table and reduced. A single envelope can be constructed from the poles that remain.

The possibility exists that a single waveform could be constructed from multiple measurements during both lightning and EMP transient testing at the system level. The aircraft could be instrumented and measurements taken during EMP testing. The same sensors would remain in place when the aircraft is moved and subjected to lightning tests. This waveform could then be re-injected at the box level to produce an acceptable result. This approach may have instrumentation limitations at present, but will become more practical as broadband sensors and injection probes are developed.

3. CONCLUSIONS

1. The present EM transient specifications, test requirements, and test techniques have developed piecemeal over the years for each of the E^3 elements. They have been tailored by experience, operational needs and test capabilities, and place artificial constraints on identifying possible test overlaps. Unless some attempt is made at rewriting current test requirements to reflect a more integrated environment and a more effective use of modern test and evaluation capabilities, the amount of test reduction possible will remain limited.

2. Transient testing (EMP, Lightning, and ESD) has potential overlap at the box and system levels. However, direct comparisons among presently specified environments, test requirements, and methods of performing tests are difficult. Therefore, the specific tests need to be further reduced into similar parameters for direct comparisons and reduction of test overlaps.

3. A review of test configurations provided a Reduced Test Configuration Table (Table 6). Applying additional factors such as assuming the availability of common instrumentation and the changing of test methods helped to identify potential test groupings and possible test reductions. The possible groupings are: (1) various EMP tests and the lightning T02, T03 and T05 tests and (2) both of the ESD tests and the lightning T05 test.

4. All transient waveforms, both at the system level and at the box level, are comparable in terms of the five commonly used norms. However, such comparisons at the system level would be of little use to the significant differences in specifying system test environments.

5. Transient induced characteristics from ESD, EMP, and lightning are similar at the box level. Norms provide a technique for measuring the effectiveness of

composite bounding waveforms which are developed to provide a single, direct-drive waveform for testing ESD, EMP, and lightning effects at the box level.

6. Bounding waveforms or waveform envelopes can be developed from measured data at the box level. Two techniques (AR and DSC) should be investigated to develop such envelopes.

7. The direct-drive waveform envelope test approach must be addressed carefully. Such an approach might lead to some overdesign or overly stressful testing based on current test requirements across all transient testing. However, the approach also offers the possibility of providing a more accurate, consolidated waveform to determine aircraft survivability.

4. RECOMMENDATIONS

1. A basic review or investigation of E^3 environments, requirements, and test capabilities should be undertaken. It should not be restrained by official requirement documents and specifications. The objectives would be: (1) to make more effective use of modern test and measurement capabilities to provide information and data, and (2) to seek an integrated approach to E^3 requirements and specifications.

2. The instrumentation requirements and test methodologies needed to combine (1) EMP tests and Lightning TO1, TO3, and TO5 tests and (2) both of the ESD tests and the Lightning TO5 test should be identified. Needed instrumentation development programs should then be pursued. The objective would be to demonstrate the testing methodology and techniques needed to satisfy the combined test requirements.

3. The two techniques (AR and DSC) for developing waveform envelopes should be investigated using Norms to measure the effectiveness of each and to serve as a measure of any incremental improvements or new developments. The first step would be to use data from EMP tests. If successful, waveform envelopes based on data from lightning and ESD tests should be investigated. The final step would be the combination of all of the waveform envelopes into a single, integrated, bounding waveform.

APPENDIX A. ENVIRONMENTAL EFFECTS REDUCTION

The approach used in the test reduction investigation is shown in Figure 1. In this appendix, effects due to all electromagnetic environments are reviewed initially. A matrix approach was selected because of its flexibility in allowing the visual comparison of many similar items. After general matrices for system-level and box-level effects are developed, the study is restricted to transient environments and reduced transient matrices were developed.

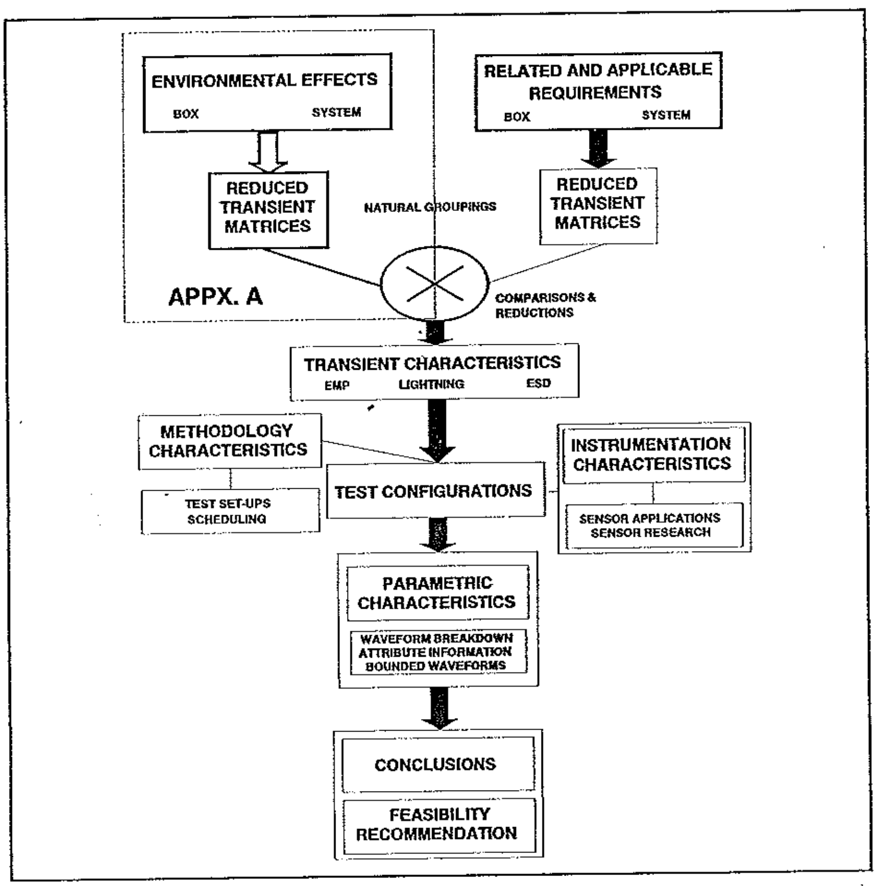

Figure 1. Flow of this Study Section

1. ELECTROMAGNETIC TEST ENVIRONMENTS

MIL-HDBK-237A and the SPAWAR generated Draft Electromagnetic Compatibility Standardization (EMCS) Program Plan identified a set of EMC specification documents to be used during concept validation, full scale development, and production. These matrices shown in Tables 1 and 2 were developed from these documents.

The matrices identify natural environmental groupings that help enable further reductions in the overall matrix structure. They compare the E^3 environments against a list of conditions identified as "effects". These effects are in reality the type of phenomena (CE, RE, CS, RS) the environment appears as when it is being evaluated. Each effect may take various forms for a specific environment. These forms are identified as modulated (MOD), continuous wave (CW), bursts of CW, or as transients.

There was a complication with the use of a single environment matrix for all conditions. Some environments can appear differently at the box-and system-level. For instance, EMP initially appears as a radiated environment to the aircraft, but can reach the box level as a radiated or conducted transient. Other environments, such as EMC and EMI, can appear as different environments to boxes other than the one evaluated. Therefore, because of the differences, and since some test requirements also differ at the box and at system levels, both levels were investigated.

Notice in Tables 1 and 2, the overall flow of X's runs from to left to bottom right, and from modulated signals to transients. This structure produces groupings which can be used to indicate which requirements and test methods should be compared for similarities and subsequently reduced. However, a complete reduction must also involve a corresponding combination of environments, test requirements, specifications, and test technologies.

Table 1. Box-Level Effects Comparison Matrix

ENVIRONMENT	EFFECTS							
	CE	RE	CS	RS	MOD	CW	BURST	TRANS
TEMPEST	X	X			X			
EMC/EMI*	X	X	X	X	X	X		X
EMV**			p	X	X	X	X	
RADHAZ		X						
HERO			P	X	X	X		
HERF			X	X			X	
EMCON		X			X	X	X	
HPM				X	X	X	X	
EMP			X	X				X
ESD			X					X
P-STATIC***								X
LIGHTNING****			X					X

*	Combinded for convenience.
**	Indicates environment defined many ways and changes periodically when new radars or communications systems are developed. Uses RS03 test methods.
***	P-Static is a system environmental effect which can impact box-level operation.
****	Although Corona is similar to P-Static, is included with lightning only because it is incorporated within a lightning requirements specification. P-Static is much higher in frequency then Corona.
P	Indicates could be tested in this manner but currently not used. The technique would involve a re-injection of a previously measured system-level threat. The current techniques used will be discussed later in this paper.
CE	Conducted Emission
RE	Radiated Emission
CS	Conducted Susceptiblity
RS	Radiated Susceptibility
MOD	Modulated Susceptibility Source
CW	Continuous Wave Susceptibilty Source
BURST	Bursted CW Susceptibility Source
TRANS	Transient Type Phemnomena

Table 2. System-Level Effects Comparison Matrix

ENVIRONMENT	EFFECT							
	CE	RE	CS	RS	MOD	CW	BURST	TRANS
TEMPEST		X			X			
EMC/EMI	X	X	X	X	X	X		X
EMV*			P	X	X	X	X	
RADHAZ		X						
HERO				X	X	X	X	
HERF			P	X			X	
EMCON		X			X	X	X	
HPM				X	X		X	
EMP				X				X
ESD			X					X
P-STATIC			X					X
LIGHTNING			X	X				X

* Indicates environment defined many ways and changes periodically when new radars or communications systems are developed. Uses RS03 test methods.

P Indicates could be tested in this manner but currently not used. The technique would involve a re-injection of a previously measured system-level threat. The current technique used will be discussed later in this paper.

2. TRANSIENT ENVIRONMENTS

Looking at the natural groupings on Tables 1 and 2, transient environments are easily identified. Eliminating all but transient environments results in the first tier reduction for box- and system-level effects as shown in Tables 3 and 4.

EMI and EMC could in some respects be considered generic environments. The transient form identified in the tables under EMC/EMI relates to EMP only. Therefore, for the transient reduction, these environments can be removed as a separate item and considered hereafter under the EMP environment.

Table 3. Box-Level Transient Effects Comparison Matrix

*ENVIRONMENT	EFFECTS							
	CE	RE	CS	RS	MOD	CW	BURST	TRANS
EMC/EMI	X	X	X	X	X	X		X
HERO**			P	X	X	X	X	X
EMP			X	X				X
ESD***			X					X
LIGHTNING			X					X

* Note: P-Static has been removed because box-level effects are a direct result of the P-Static environment interacting at the system level i.e., testing and fixes only occur at the system level.

** Note: HERO is a destructive test and is only listed here for completeness as a transient analysis threat. Also, conducted susceptibility is not a HERO test requirement but is often used to direct energy to the EED for analysis. In some cases, the Radiated Emission from a system-level measurement are also re-injected to a box using direct drive for analysis.

** The 300 KV requirement for hovering aircraft is not a box-level threat.

Table 4. System-Level Transient Effects Comparison Matrix

ENVIRONMENT	EFFECTS							
	CE	RE	CS	RS	MOD	CW	BURST	TRANS
EMC/EMI	X	X	X	X	X	X		X
HERO*				X	X	X	X	X
EMP				X				X
ESD			X					X
P-STATIC			X					X
LIGHTNING			X	X				X

* analysis only

A further matrix reduction of similar effects and phenomena can be performed on those box- and system-level environments involving transients. The results are shown in Tables 5 and 6.

Table 5. Box-Level Reduced Effects Comparison Matrix

ENVIRONMENT	EFFECTS					
	CS	RS	MOD	CW	BURST	TRANS
EMP/ESD/LIGHTNING	X					X
EMP*		X				X

* although the environment is radiated and referenced to an EMC/EMI document, at the box level some testing is conducted

Table 6. System-Level Reduced Effects Comparison Matrix

ENVIRONMENT	EFFECTS					
	CS	RS	MOD	CW	BURST	TRANS
ESD/P-STATIC/LIGHTNING	X					X
EMP/LIGHTNING*		X				X

* although the environmental threat for indirect effects is radiated, the test for this environment is conducted

Based on the reduced environment comparison matrix, a further reduction between box and system level testing may by possible. This is particularly true when an environment at the system level can be duplicated at the box level during testing. The subject of re-injection testing at the box level is covered in Appendix C.

3. CONCLUSION

From the matrix reduction effort, three environmental effects overlaps are visible. Initial potential reduction possibilities include EMP/ESD/lightning conducted susceptibility at the box level, ESD/P-Static/lightning at the system level, and EMP/lightning at the system level.

APPENDIX B. TEST REQUIREMENTS INVESTIGATION

Following the initial environmental groupings, all naval aircraft related E^3 requirements documents are similarly evaluated and reduced. Although not specifically addressed herein, this review also included related non-Navy test documents. Figure 1 indicates the portion of the study covered in this section.

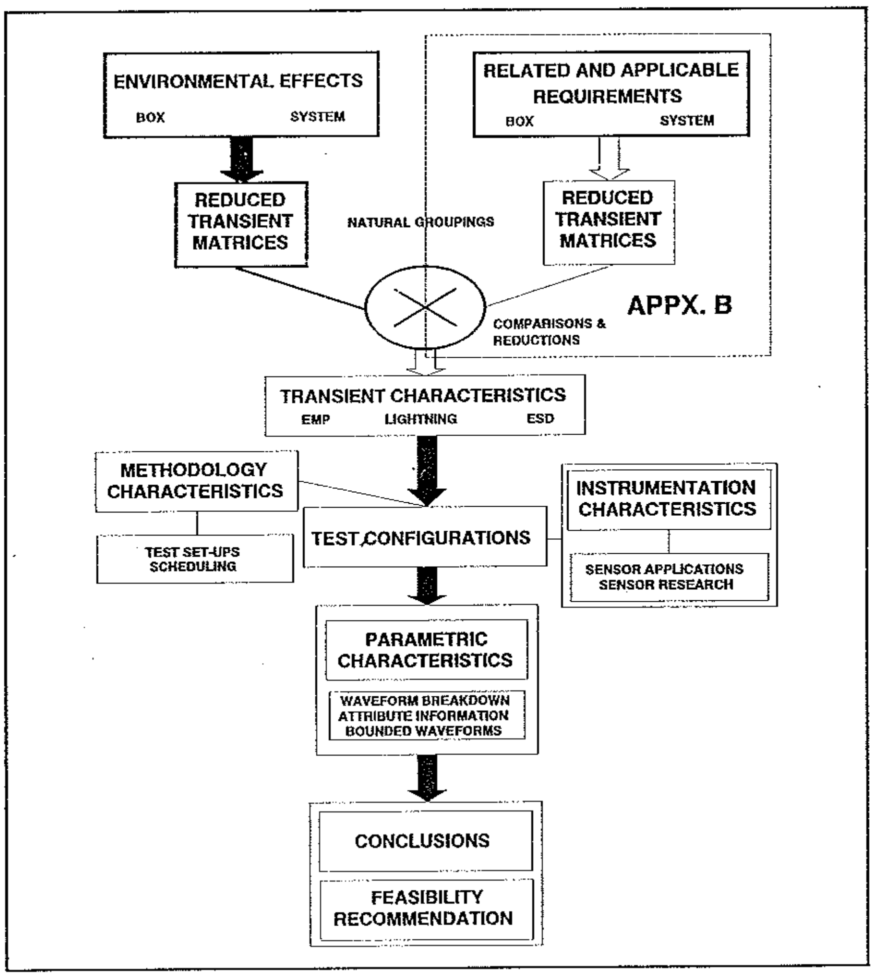

Figure 1. Flow for this Section

1. TEST REQUIREMENTS

Research revealed a number of documents that list certification requirements, test methods, and design techniques for ensuring valid protection against each of the EM environments. Some documents, although not related to aircraft testing, offer approaches which might provide further insight to this study. For instance, MIL-188-125 describes a topology approach for ground based facilities hardening. It suggests that the hardening topology used is really the determining factor for the level at which testing can be applied to provide valid system results. Using this alternative approach, performance verification tests are based on shielding and attenuation measurements, not direct exposure to multiple environments.

Another point from the document review is that part of the inability to integrate testing at the system level is the failure to define ideally an integrated system environment. Environments interacting with the system often manifest themselves differently or in multiple ways at the box level.

Documents related to Navy aircraft are listed in Table 1.

1.1 Breakdown of Requirements by Transient Effect

Several tests, derived from various documents, are necessary to fully evaluate an aircraft's susceptibility profile. Each test is intended to qualify a specific aspect of the electromagnetic spectrum, with the sum of all testing used to verify susceptibility hardness. Tables 2 and 3 break each environmental test into specific requirements and reference documents.

Table 1. Requirements Documents

REQUIRED DOCUMENTS	
MIL-STD-331B	Fuze and Fuze Components, Environmental and Performance Tests for (preliminary ESD document)
MIL-STD-449	Radio Frequency Spectrum Characteristics, Measurement of
MIL-STD-461C	Electromagnetic Interference Characteristics, Requirements for Equipment
MIL-STD-469A	Radar Engineering Design Requirements, Electromagnetic Compatibility
MIL-STD-1385B	Preclusion of Ordnance Hazards in Electromagnetic Fields, General Requirements for (HERO test document)
MIL-STD-1757A	Lightning Qualification Test Techniques for Aerospace Vehicles and Hardware
MIL-B-5087B	Bonding, Electrical, and Lightning Protection, for Aerospace Systems (B for bonding and P-static, A for corona)
MIL-E-6051D	Electromagnetic Compatibility Requirements, Systems
MIL-D-0129D	Dischargers, Electrostatic, General Specification for
MIL-STD-1795A	Lightning Protection of Aerospace Vehicles and Hardware
DOD-STD-2169	High Altitude Electromagnetic Pulse (HEMP) Environment (this is the primary HEMP test document)
MIL-HDBK-235-1	Electromagnetic Radiated Environment Considerations for Design and Procurement of Electrical and Electronic Equipment (235-2A primary E^3 test environment document)

Table 2. Box-Level Transient Test Requirement

TEST	EFFECTS					
	CS	RS	MOD	CW	BURST	TRANS
EMC/EMI 461	X	X	X	X		X
EMP	X	X				X
ESD Group F 331* 9129**	X					X
LIGHTNING***	X					X

Note: The above specifications may list additional requirements other then electromagnetic requirements.

* Same test at box or system level.

** MIL-D-9129D is a discharger only requirement that can be satisfied by test method MIL-STD-1757 TO2, Zone 2.

*** A box-level lightning test requirement would be a direct drive test derived from the system level data. Otherwise, MIL-B-5087B requirements are applicable at the box level. Corona is a system only test.

Table 3. System-Level Transient Test Requirement Matrix

TEST/SPEC	EFFECTS					
	CS	RS	MOD	CW	BURST	TRANS
EMC/EMI 6051/461 RS05	X	X				X
EMP/461 RS05		X				X
ESD 331 Group F	X					X
P-STATIC/CORONA* 5087/1757	X					X
LIGHTNING 1757 DIRECT & INDIRECT	X					X

* The 5087B requirement is related to bond impedance. Tests for the correct bond impedance are not the intent of this study. P-Static tests are intended to determine if receiver noise due to P-Static is greater then - 10 dBm. Also, corona is listed in this field now because of similarity, although the corona test requirement is specified in a lightning document.

Note: Concerning the 461 RS 05 EMP test, this test is applied at box or system level. The radiated system-level pulse induced at the box level can be duplicated and re-injected directly to a test item using direct drive.

1.2 Test Requirement Documents

Based on the specifications called out in Tables 2 and 3, each requirement document is further broken down as indicated in Table 4. Only those sections of the requirement documents that relate to electromagnetic effects are identified. Table 4 lists information on all transient type testing for completeness, even though only lightning, EMP, and ESD will be considered further.

MIL-B-5087B, MIL-E-6051D, and MIL-STD-1757A are considered as First Tier documents. First Tier documents are contractually binding. MIL-B-5087B and MIL-E-6051D are included here for completeness. Spike phenomena is not considered further in this study. MIL-STD-1795A is included here since it describes the theoretical environment and provides the basis for the lightning tests called out in MIL-STD-1757A.

Table 4. Breakdown of Required Documents for Transient Testing

STANDARD	METHOD	SECTION	SPECIFICS
MIL-E-6051D	CS	3.2.3.1 Safety Margins 3.2.7 Spikes	<6dB or <20 dB explosives spikes >50 usec duration shall not exceed +50/-150% for ac powerlines
		3.2.10 Static Electricity	Ref: AFSC 80-9 vol. 4
		2.3.11 Personnel Hazard	Ref: MIL-STD-454
		3.2.12 Ordnance	Ref: MIL-P-24014
MIL-STD-1757A Lightning	CS	TO1 Attachment Pt. TO2 Direct Eff. Structure TO3 Direct Eff. Vapor TO4 Corona TO5 Indirect (primary)	Waveforms A,D Waveforms A, B, C, D Waveforms A, B, C, D Waveform B Waveform E
MIL-STD-1795A Lightning	CS	Ideal Waveform Extrap.	Double-Exponential Waveform
MIL-STD-331B ESD	CS	F1 Electrostatic Disc.	Human-Body 25 kV Waveform Air Replenishment 300 kV Waveform
MIL-STD-461C	CS	CS 11 (bulk cable)	10 kHz - 100 MHz
EMP	RS	RS 05 (various methods)	Double Exponential Waveform

CS Conducted Susceptibility
RS Radiated Susceptibility

MIL-STD-461C represents a generic test document for many electromagnetic environments. EMP tests are applicable to any configuration from box to platform. Box-level tests requirements for MIL-STD-461C were determined by environmental evaluation and statistical comparisons of many responses. The intent was to develop a lower-level electromagnetic environmental test applicable at the box level for manufacturers of equipment. For this study, transient radiated RS05 testing for EMP can be applied to a box or system. Naval system-level aircraft testing is an RS05 type of test. However, it is important to note that a pin injection test at the box level has been recognized as useful in EMP testing. Appendix E re-examines this concept.

MIL-STD-461D, currently under review, is expected to delete the EMP pin injection test.

Reducing Table 4 to only those tests used for Navy aircraft transient applications produces the final breakdown of required tests shown in Table 5.

Table 5. Summary of Required Transient Tests

SPECIFICATION	METHOD	TEST	WAVEFORM
MIL-STD-1757A Lightning	CS	TO2 Direct Eff. Struct. TO3 Direct Eff. Vapor TO5 Indirect (primary)	Waveform A Waveform A Waveform E
MIL-STD-331B ESD	CS	F1 Electrostatic Discharge	Human-Body 25 kV Waveform Air-Rep. 300 kV Waveform
MIL-STD-461C EMP	RS	RS05 (various methods)	Double-Exponential Waveform

APPENDIX C. TRANSIENT WAVEFORM TEST CHARACTERISTICS

Using the previous reductions as a basis, each Naval aircraft transient test is evaluated in terms of its test waveform requirements and also how it is actually applied during testing. The objective is to compare requirements and simulation waveforms for transient-type tests on an equal basis if possible. Figure 1 indicates the portion of the study covered by this Appendix.

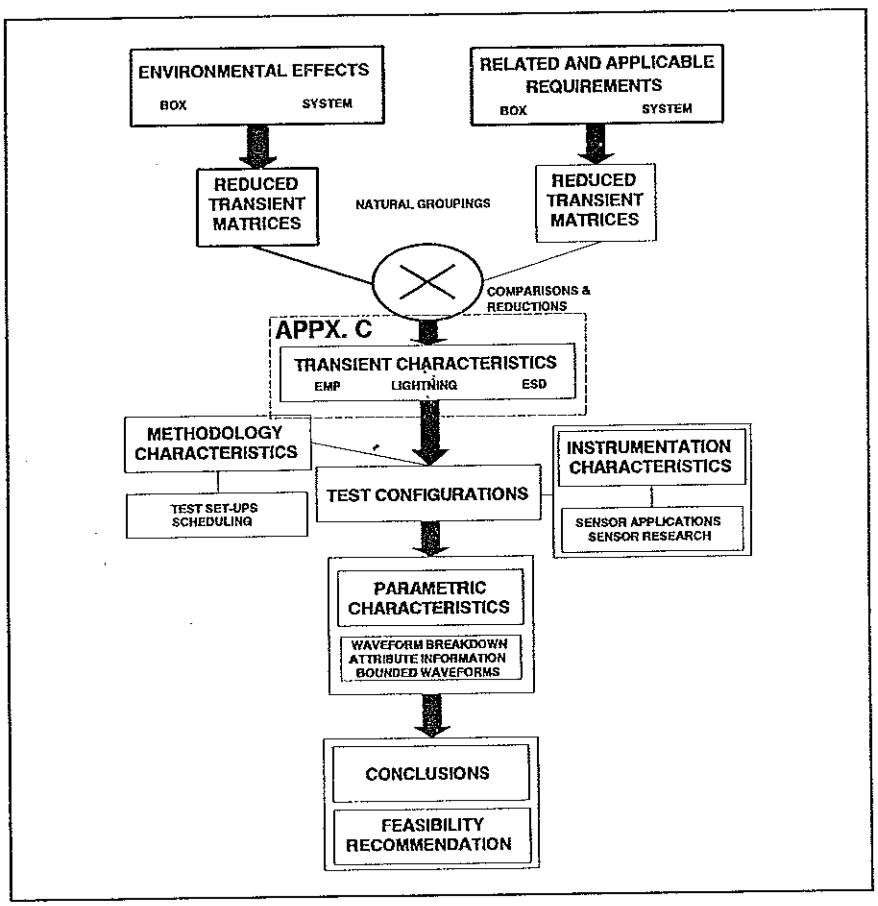

Figure 1. Flow of this Study Section

1. TRANSIENT CHARACTERISTICS

This section presents detailed information on lightning, EMP, and ESD transient test techniques and waveform characteristics.

1.1 General Transient Testing

The basic approach for aircraft transient effects testing is depicted in Figure 2. The instrumented aircraft is exposed to a simulated external environment from one or more locations. Internal system responses to this environment are measured. If the simulated environment is less than predicted from the actual environment, measurements are extrapolated to their expected level. The measured or extrapolated response is considered the system stress, and sets the system level of susceptibility to the external environment. Inherent within the stress waveform is the transfer function from the system to the measurement point. The initial test is usually administered in a simulated power-on mode.

Next in the test cycle, the same test point responses (cable responses) are recreated at the extrapolated level, and reinjected at increasingly higher levels into the avionics equipment. The reinjected signal is increased until the system upsets, fails, or a reasonable safety margin above the full specified requirement is achieved. This is called the "direct-drive" approach discussed in the next section. The level required to cause upset is considered the system strength, and the margin of survivability is defined as the system's strength divided by its stress.

1.2 The Lumped-Element Approach and Direct Drive

The complex interrelationship between physical location, coupling modes, and various external environmental responses is difficult to understand. Direct-drive testing reproduces the system-level response characterization at a specific test point. The intent is to concentrate on measured data at the point in the system where the response is critical, and not worry about environments which are applied external to the system, or

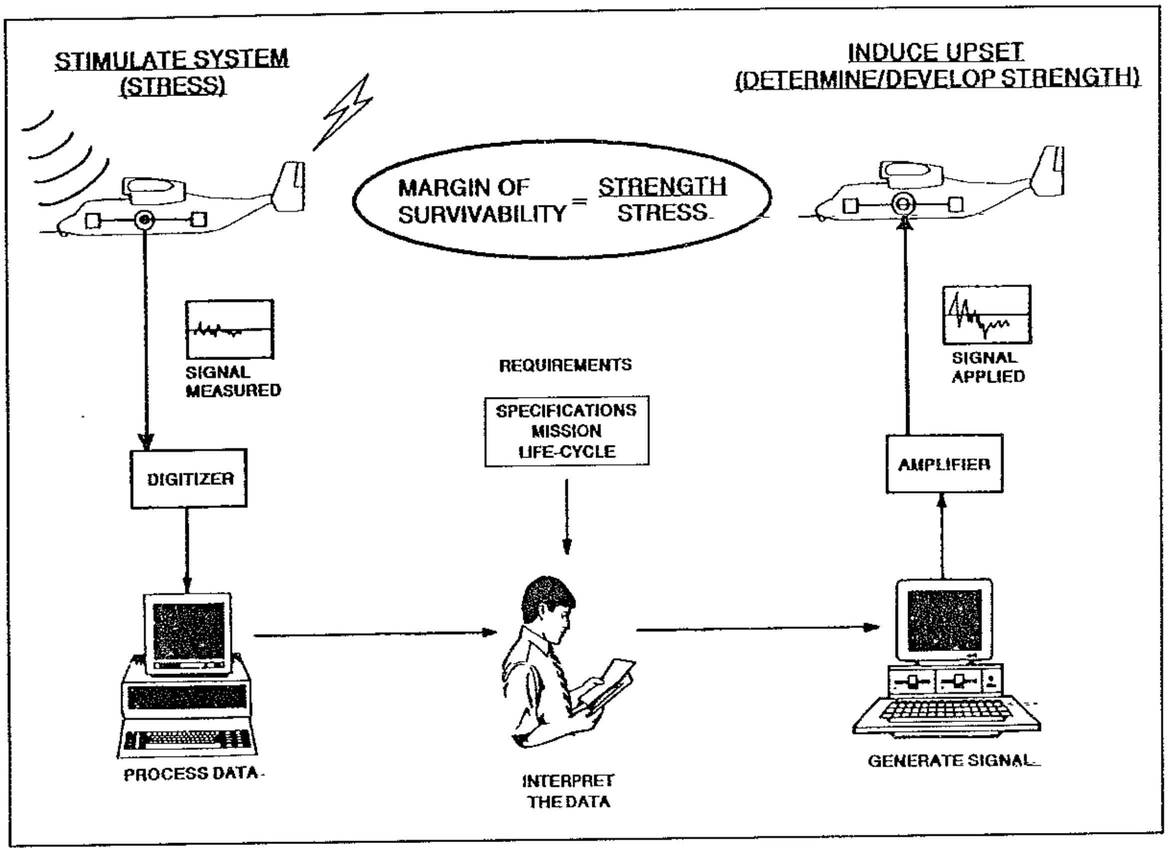

Figure 2. The Electromagnetic Transient Evaluation Process

how their effects get to the test point. This objective is met in transient testing by using a lumped-element network approach.

Shown in Figure 3, the lumped-element approach allows the use of direct-drive techniques to replace the external source. Direct-drive testing can be thought of as an application of Norton's Theorem[1].

[1] Norton's Theorem states: "Insofar as the external characteristics are concerned, a two-terminal electrical network containing sources and passive elements is equivalent to a current source in parallel with the network with all sources removed: the current of the current source has the same magnitude and reference direction as those of the current which would exist at the terminals in the original network if the terminals were short circuited."

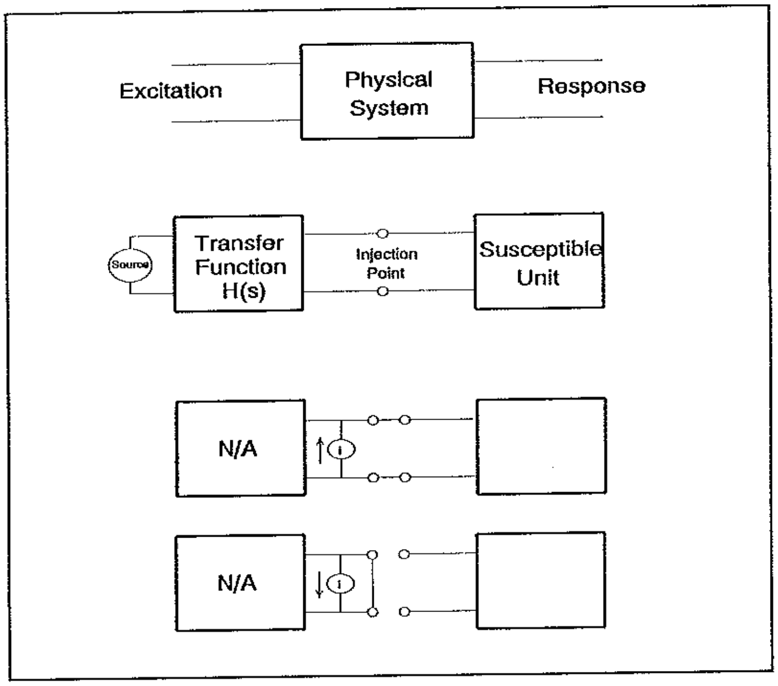

Figure 3. Norton's Theorem Equivalent Circuit

2. LIGHTNING

The following sections discuss lightning test techniques and characteristics in detail. ESD and EMP testing will be covered in less detail due to their similarities.

The waveform specified in lightning document MIL-STD-1795A (Figure 4) is theoretically ideal. Actual test waveforms do not need to duplicate the ideal, only one or more of its primary electrical parameters. Aircraft lightning tests use waveforms that create responses easily extrapolated to the ideal.

2.1 MIL-STD 1757A Lightning Voltage Transients

MIL-STD-1757A identifies four lightning voltage waveforms, A, B, C, & D. For lightning qualification testing, primarily three voltage waveforms are used: A, B and D. Waveforms A and D are used to test for puncture and potential attachment points. Waveform B is used to test for streamers. Waveform C is used for scale model testing,

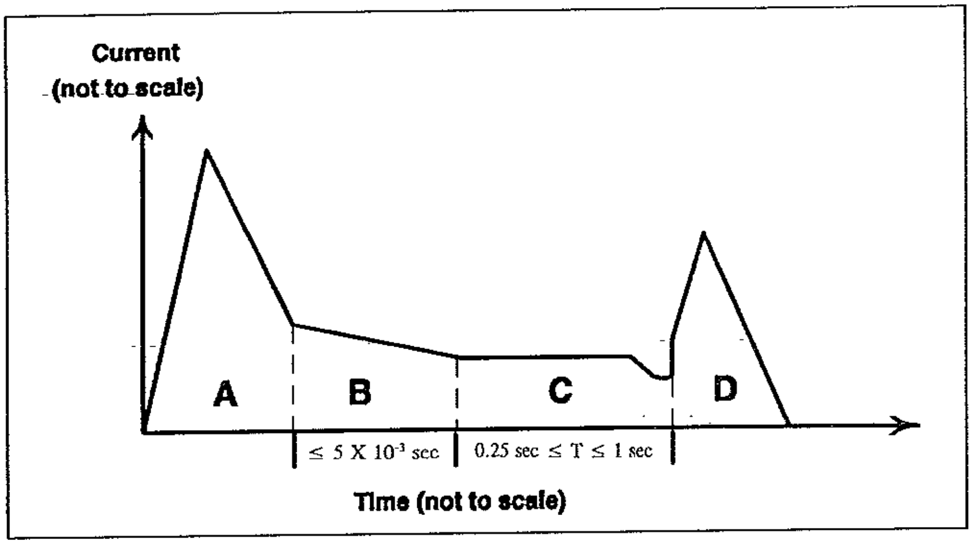

Figure 4. Components of the Theoretical Lightning Current Waveform (MIL-STD-1795)

and is not often employed. Waveform D is a slow-fronted waveform used to provide a higher strike rate to the low probability regions than otherwise might have been expected. Since no similar voltage tests are identified for other transient phenomena, nor are they used in Navy aircraft testing, these waveforms are not considered further in this study.

2.2 MIL-STD-1757A Lightning Current Transients

For qualification testing, there are four main current waveforms (A, B, C, and D) used to determine direct effects. These waveforms represent the four components of the theoretical lightning waveform (from MIL-STD-1795A). One additional waveform (E) is used for indirect testing. At present, only waveforms A and E are used for Navy aircraft testing. Current waveforms are used herein to compare lightning, EMP, and ESD characteristics. Waveforms can be applied individually or as a composite waveform.

Figure 5 is the current waveform (A) used for direct-effects testing and Figure 6 is the corresponding frequency domain plot. Figure 7 is the current waveform (E) used to evaluate indirect effects.

2.3 Lightning Test Approach and Test Waveforms

Five test methods (TO1 through TO5) are intended to verify, through lower-level, non-destructive testing, the various protection techniques that have been applied to aircraft which could encounter the full (ideal) lightning waveform. TO1 is an attachment point test with voltage (rather than current) waveforms. T04 uses voltage waveform B for corona and streamer testing. For Navy testing, T02 and T03 testing is performed with current waveform A, and T05 testing is performed with current waveform E.

Since the equipment used for lightning tests varies between facilities, MIL-STD-1757A allows for some flexibility related to how each waveform is generated. There are three different techniques that can be used to achieve the objective of each test method as follows:

1. Use current waveforms which have the same waveshape as the ideal but are smaller in amplitude. However, the larger the scale factor between test and ideal, the less direct linearity for scaling can be assumed.

   Note: for indirect effects, in equation 1 the double-exponential equation represents the A component of MIL-STD-1757A.

   (1)

   I_o= 218,810 amps

   α= 11,354 /sec

   β= 647,265 /sec

2. Use swept CW to obtain the frequency dependent transfer function (amplitude and phase) between the externally applied lightning current waveform and the actual internal cable response at a test point. This approach also assumes linear scaling, but includes more uncertainty than approach (a).

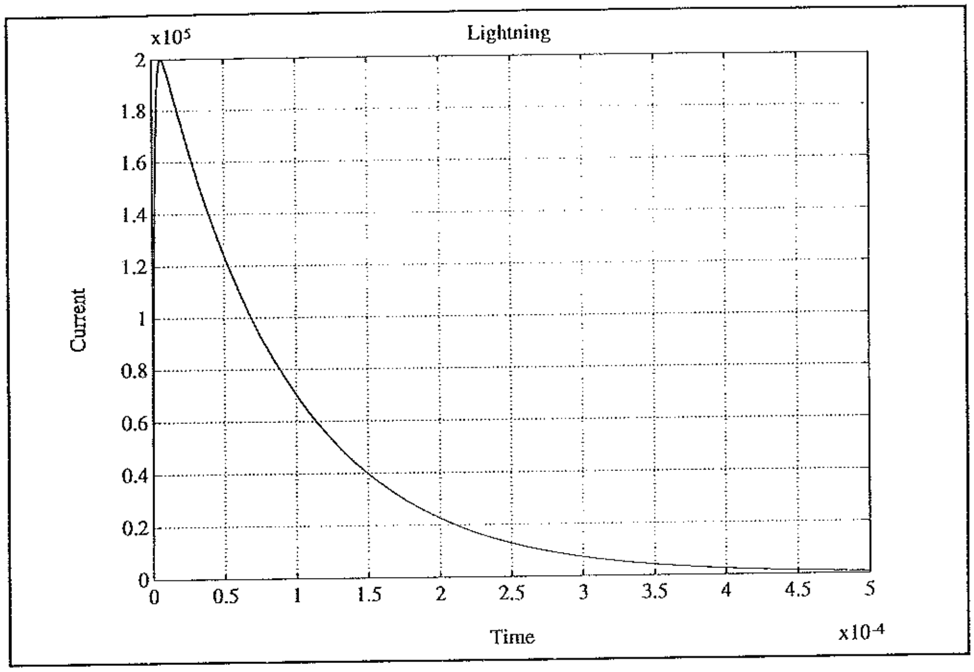

Figure 5. Lightning Current Waveform A

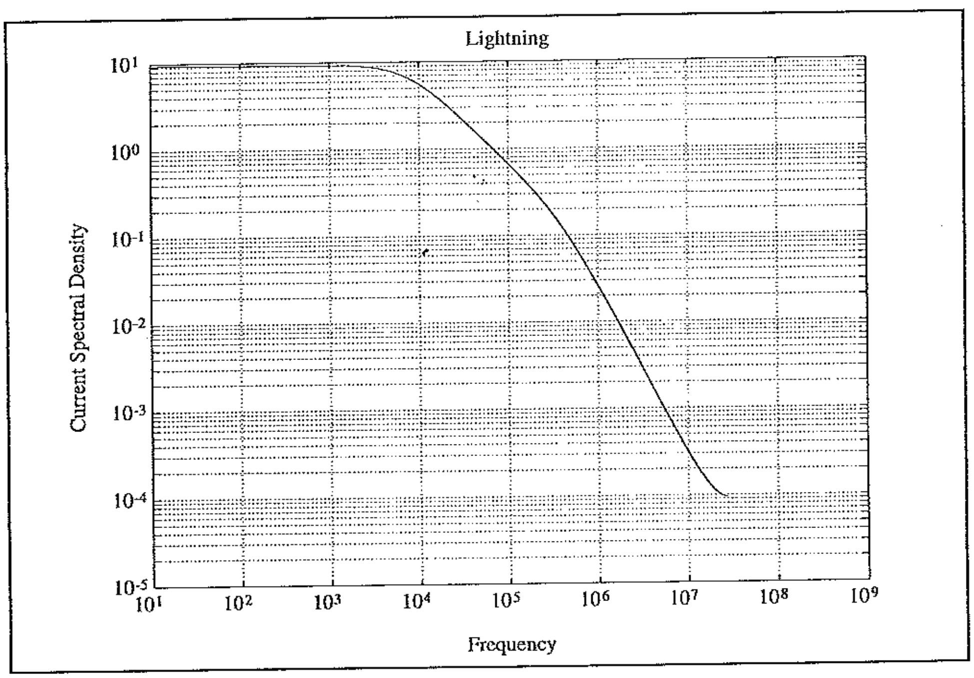

Figure 6. Lightning Current Waveform A Frequency Domain

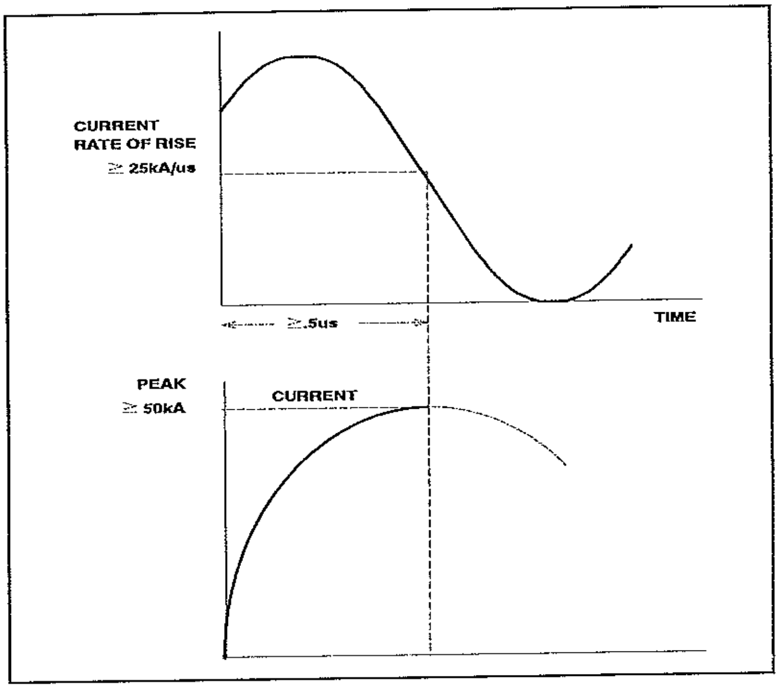

Figure 7. Lightning Current Waveform E

3. Use a damped-sinusoid generator with large i and di/dt. This technique is inexpensive, but has the disadvantage of applying a bipolar (+/-) waveform. Interpretation of the test results require knowing if the measured coupling depends principally on the peak current amplitude or the current derivative (change in current with respect to time). The damped-sinusoid waveform is shown in Figure 8.

The validity of the above techniques relates to the error caused by non-linear stress responses. Non-linear responses are beyond the scope of this study.

3. MIL-STD-331B ELECTROSTATIC DISCHARGE

This requirement is applicable to weapons which include electro-explosive devices (EED's), also called fuzes.

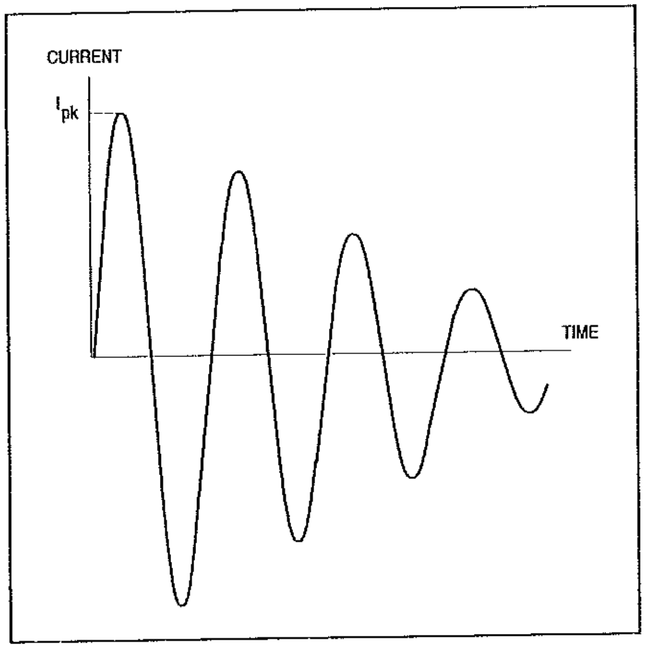

Figure 8. Damped Sinusoidal Test Waveform for Lightning

3.1 ESD Test Approach and Test Waveforms

At present, there are four tests identified in section F of MIL-STD-331B, Electromagnetic and Magnetic Influences. Of these, only subsection F1, Electrostatic Discharge, has specific test requirements called out. This is a non-instrumented, pass/fail type test. The other tests are noted as "in preparation" and relate to EMP, EMR, and lightning.

The transient ESD testing identified in subsection F1 is divided into two parts, the human-body discharge and the air replenishment discharge. Figure 9 represents the upper and lower bounds on the human-body discharge waveform developed using a capacitor and 500 ohm series resistor. This waveform is characterized by a rise time of 15 nanoseconds (10% to 90% peak value) and a fall time of 150 nanoseconds. Air replenishment discharge relates to the condition where helicopters and other hovering aircraft become electrostatically charged by ion emission from the engines or by

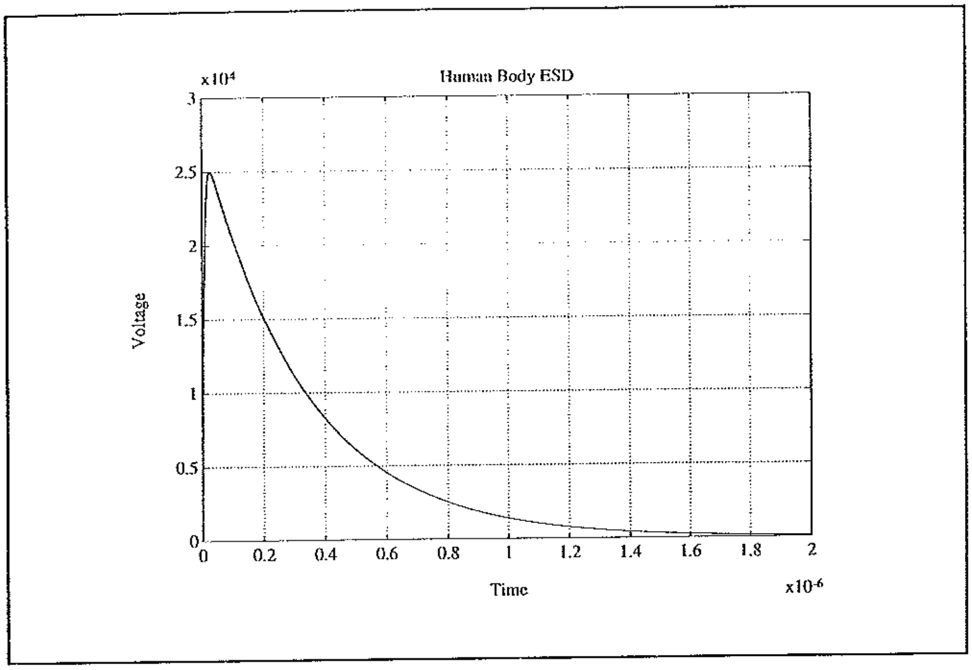

Figure 9. Human ESD Waveform

triboelectric charge separation on airfoils. Figure 10 represents the air replenishment waveform developed using a capacitor and 500 ohm series resistor.

4. MIL-STD-461/462 EMP TESTING

Two EMP tests are specified in MIL-STD-461C, one using a radiated double-exponential waveform and the other using a conducted damped sine. For Navy aircraft, only radiated tests are performed at the system level, with measured data rather than the specification value used to develop the re-injection waveform.

4.1 Conducted Transients

In MIL-STD-461C/462 EMP bulk cable conducted susceptibility testing, a damped-sinusoid transient is applied directly at the box level. CS 10 requires current injection applied directly to pins, while CS 11 requires application through bulk-current injection. As previously discussed, the damped-sinusoid transient is one of the approved test waveforms allowed in lightning testing. In lightning testing, the damped-

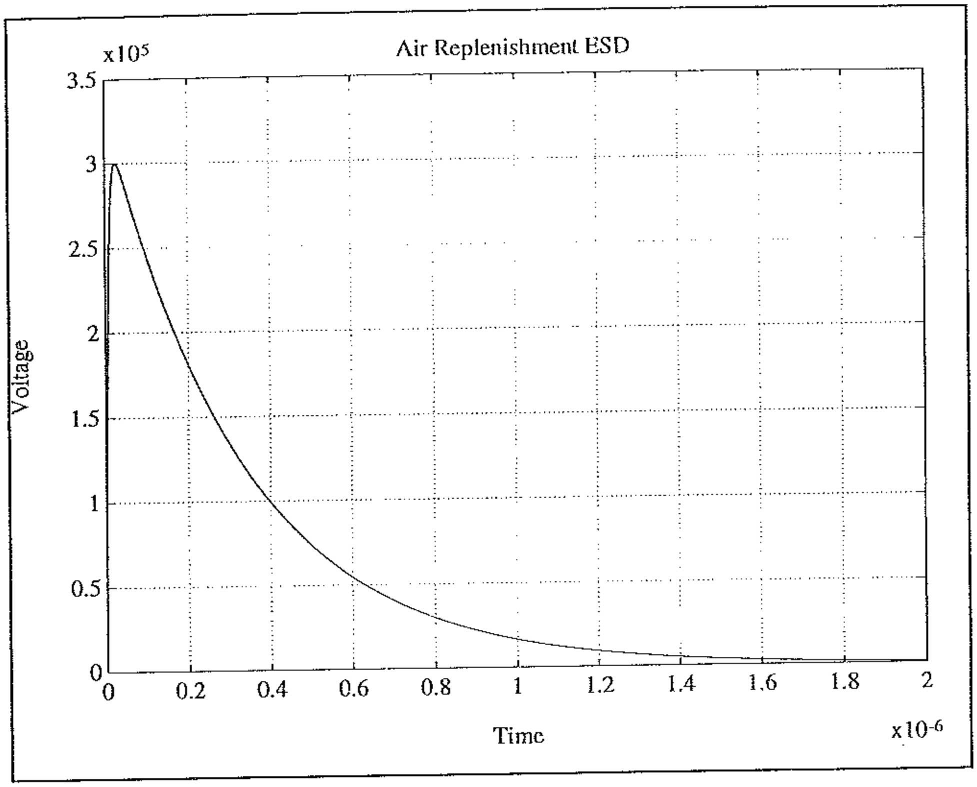

Figure 10. Air Replenishment ESD Waveform

sinusoid test is applied at the system level and responses are measured at the cable (box/port) level. Therefore, a potential test overlap exists between conducted EMP and lightning.

CS 10 and CS 11 use the damped-sine waveform described in Equation 2. The pin-injection test voltage is limited to the CS 10 level (I_{max} x 100). Also, the coupling method to the pin is inductive or capacitive depending on wire type and how the outer wire shield is grounded. For CS 11, the coupling path is inductive between 10 KHz and 10 MHz, and capacitive above 10 MHz. Bulk-current injection (direct drive) can be used for some testing of shielded wires and harnesses. The pulse repetition rate for this generator is one pulse per second.

$$I_{cable}(t) = 1.05\ I_{\max}\ e^{-\frac{\pi f t}{Q}} \tag{2}$$

$I_{cable}(t)$ = common mode cable current in amps
f = frequency in hertz
t = time in seconds
Q = decay factor = 15 +/- 5

4.2 Radiated Transients

The radiated susceptibility RS05 test is applied at the box or system level at the approximate full environment using a parallel-plate radiator or vertical dipole antenna. The size and configuration of the radiator used is related to the size of equipment tested. For a simple box, testing requires a minimum of three orientations: one with the front of the equipment facing the front of the parallel plate, one with the front turned 90 degrees towards the load end of the generator, and a final orientation with the top of the equipment tilted toward the front or back of the plate.

Aircraft testing involves four orientations and two polarizations, two orientations for vertical and two orientations for horizontal. The vehicle is tested with its major axis parallel and perpendicular to the horizontal dipole antenna, and similarly (nose-on and wing-on) with the vertical dipole antenna. The radiating sources use a double-exponential waveform specified by either MIL-STD-462 (equation 3) or by DOD-STD-2169 (equation 4). This study will address the time-domain, MIL-STD waveform only. The MIL-STD-462 (Bell Labs) waveform is shown in Figure 11, and its frequency-domain EMP waveform is shown in Figure 12.

$$E(t) = E_o \, (e^{-\alpha t} - e^{-\beta t}) \tag{3}$$

$$H(t) = \frac{E(t)}{Z_o} \tag{4}$$

$E(t)$ = Electric field in volts/meter at time t in seconds
$H(t)$ = Magnetic field in amps/meter at time t in seconds
E_o = 5.25×10^4 volts/meter
α = 4.0×10^6 /second
β = 4.8×10^8 /second
Z_o = 377 ohms

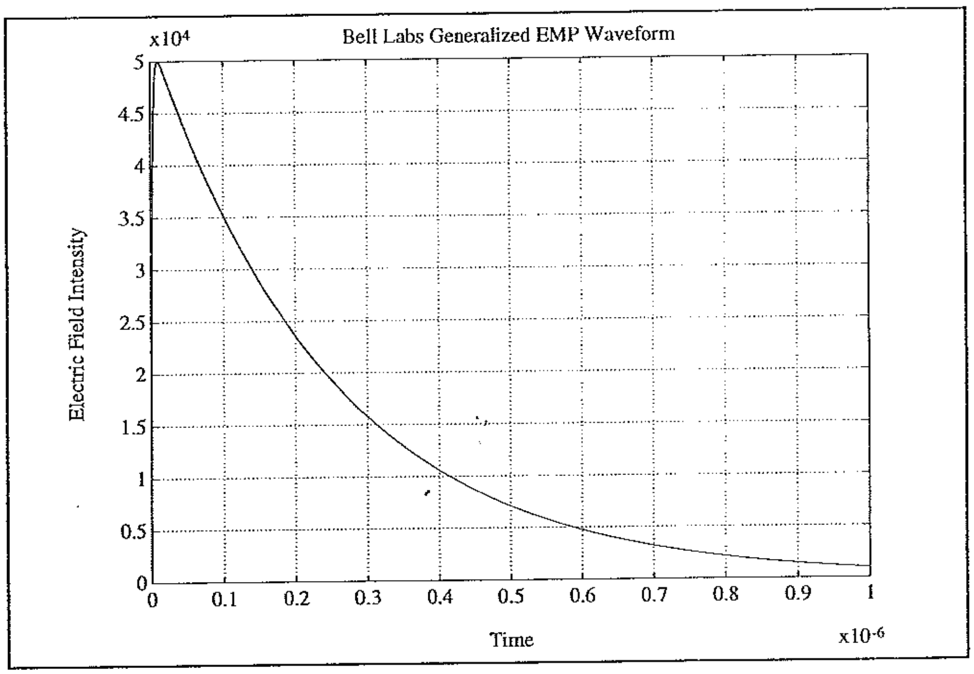

Figure 11. EMP Time Domain

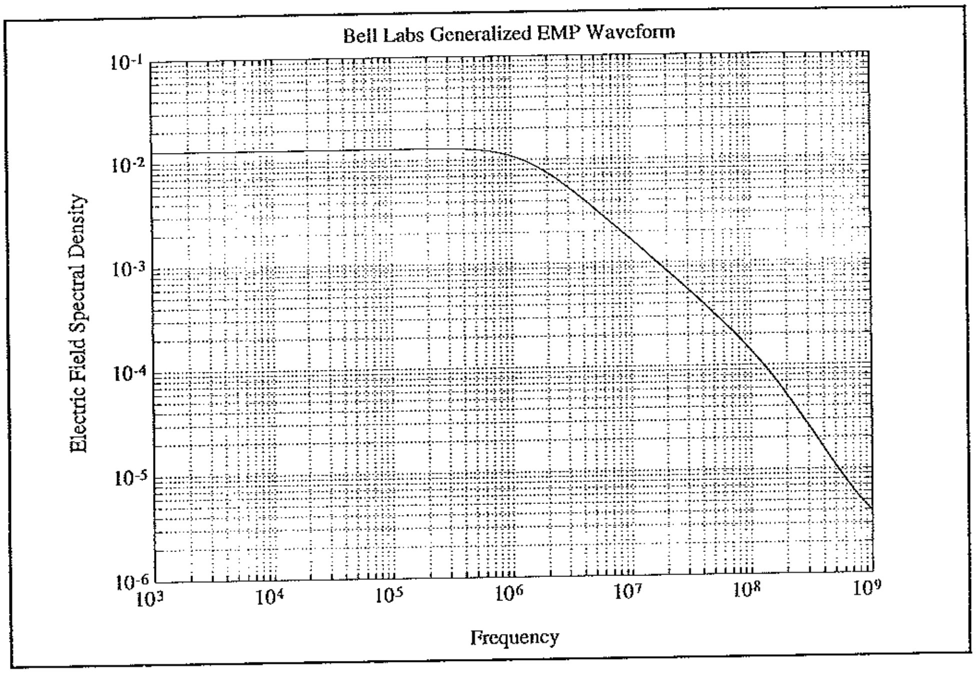

Figure 12. EMP Frequency Domain

APPENDIX D. TEST CONFIGURATIONS

In this section, the aircraft transient test process is evaluated to identify similar test or instrumentation methods which could be used for comparisons. The objective was to develop a configuration matrix based on these comparisons. Figure 1 indicates the portion of the study covered by this Appendix.

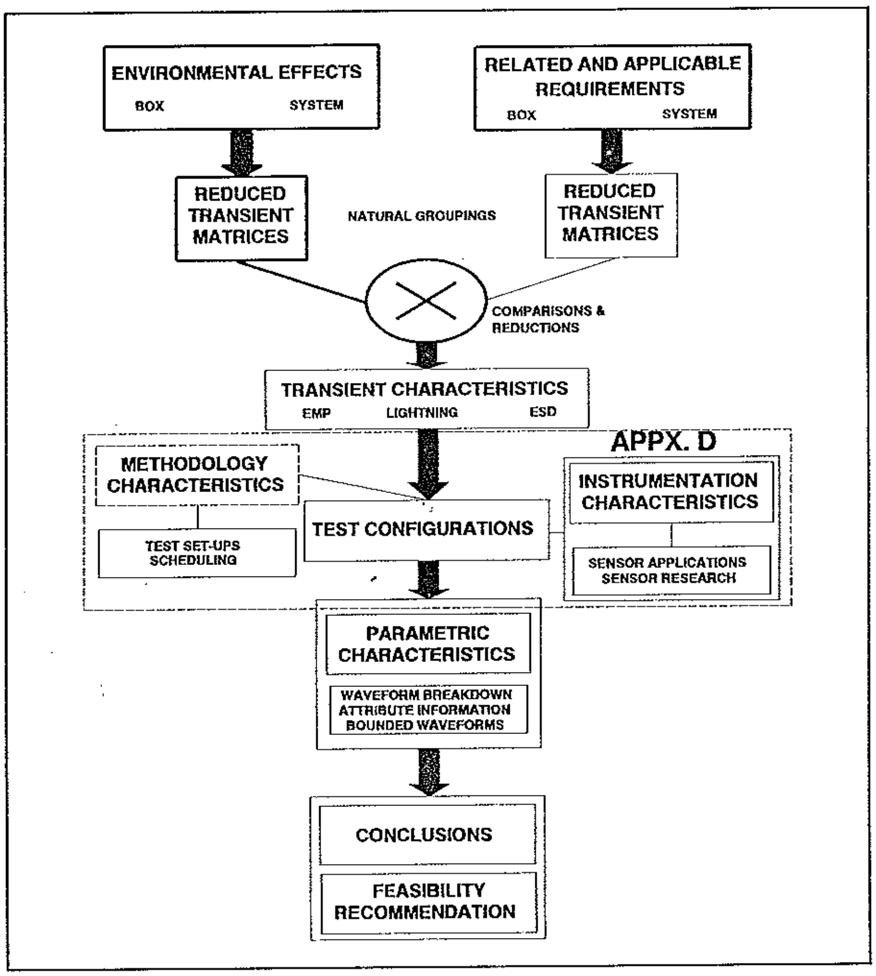

Figure 1. Flow of this Study Section

1. TEST CONFIGURATION DEVELOPMENT

This section of the study identifies common test configuration characteristics from the previous transient test information. Each "ideal" requirement waveform is compared in terms of how it is applied during testing, its frequency domain or other characteristics, and whether it is a box- or system-level test.

1.1 Potential for Test Overlap

Figure 2 shows the classic time domain overlap between lightning, EMP, and ESD transient pulses. For an equal comparison, the box-level, conducted transient was used. Figure 3 shows the frequency envelope overlaps. In each case, the waveform is a classic representation, not necessarily the actual waveform generated for test purposes. From the figures it appears that some portions of the waveforms might allow for a reduced set of tests covering all worse case conditions.

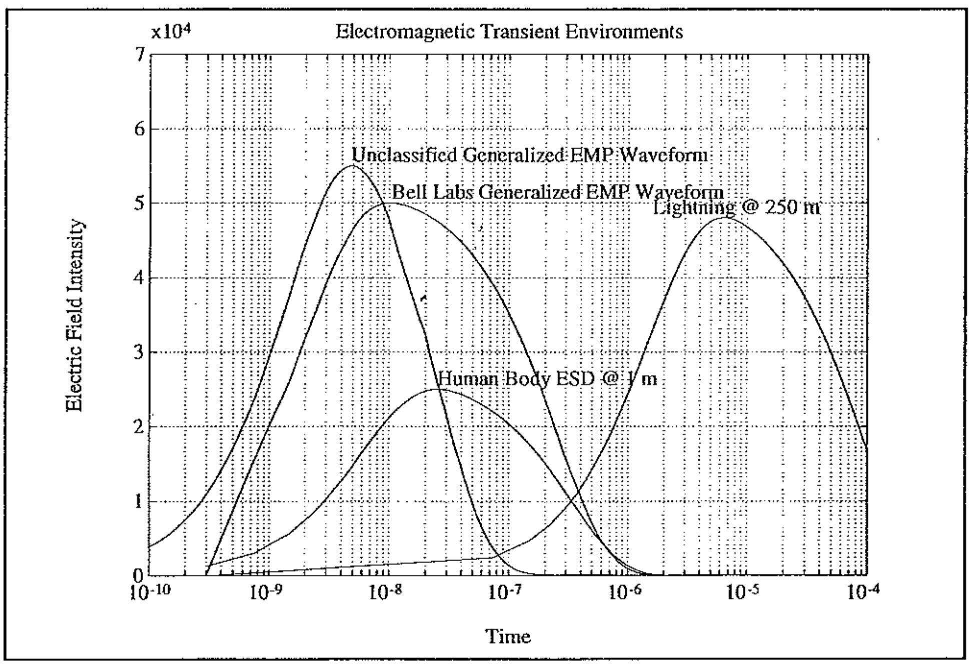

Figure 2. Time Domain Comparison of Electrical Transients for Various Threats

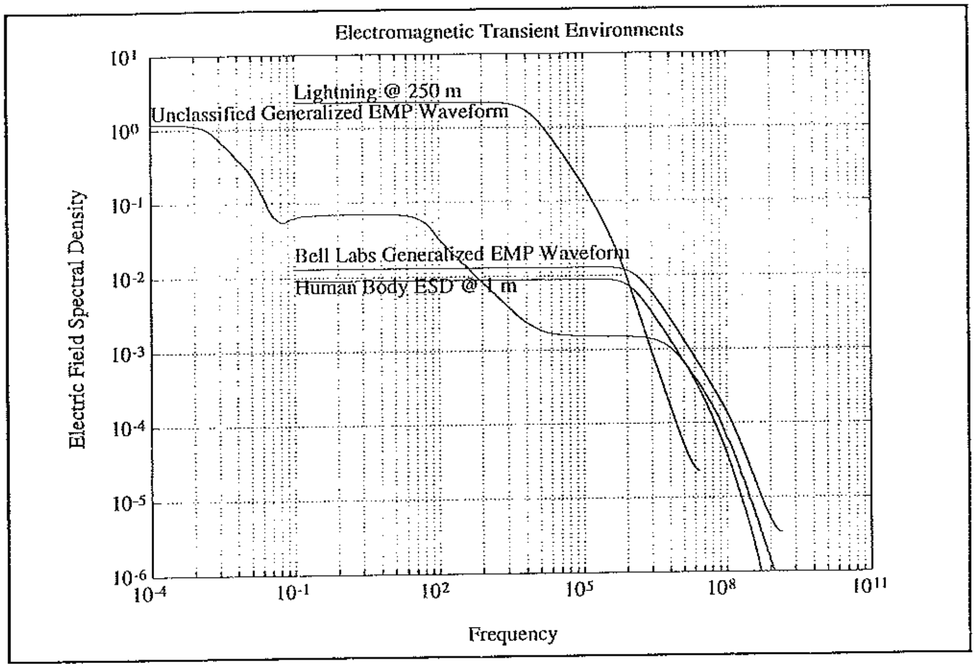

Figure 3. Frequency-Domain Comparison of Electrical Transients for Various Threats

If common frequency-domain characteristics are considered at the system level, only parts of the spectrum for various tests have overlap. This overlap is only manifested at the box level. Transient induced characteristics from EMP, lightning and ESD are similar, but the methods of generating and applying these waveforms at the system level is drastically different. Therefore, although an overlap in frequency and time might indicate the possibility for reduction, the nature of the environment as it interacts with an aircraft platform, and the current methods of simulating each threat place constraints on how a reduction could be applied.

2. SUMMARY OF TEST METHODS

Test point instrumentation is nearly identical for lightning and EMP. However, various simulation techniques are used to generate the transients. Lightning testing, for example, allows either a damped sine, a critically-damped pulse, or a cw pulse to be used to test specific systems. ESD testing uses a true critically-damped pulse because equipment is available that can support the full threat test current requirements. EMP test programs normally use a double-exponential damped sine for full radiated testing.

The rationale behind allowing various waveforms to be used for lightning tests relates to equipment availability, damage prevention, and the ability to extrapolate various waveform attributes to the maximum theoretical environments. As previously stated, extrapolation to the full environment for re-injection is common for lightning tests.

The next few figures show test locations and typical achievable waveforms actually generated during lightning tests. In this case, the waveform is a damped sine representing waveform E injected as shown in Figure 4 and measured at the location shown in Figure 5. Figure 6 shows the initially injected, corrected, raw time data from the lightning pulser. Figures 7 and 8 show typical time-domain and frequency-domain responses at an internal box that could be used for re-injection purposes.

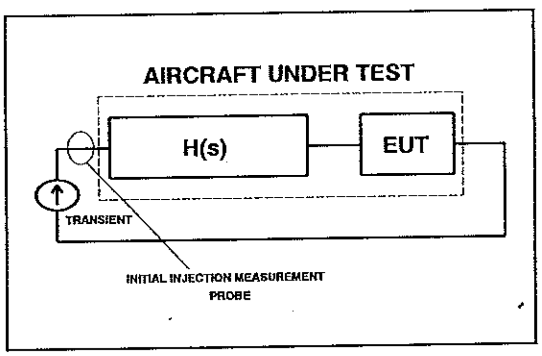

Figure 4. Pulse Injection Point

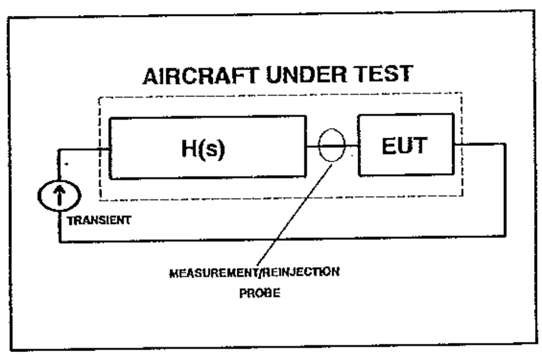

Figure 5. Response Measurement and Re-Injection Point

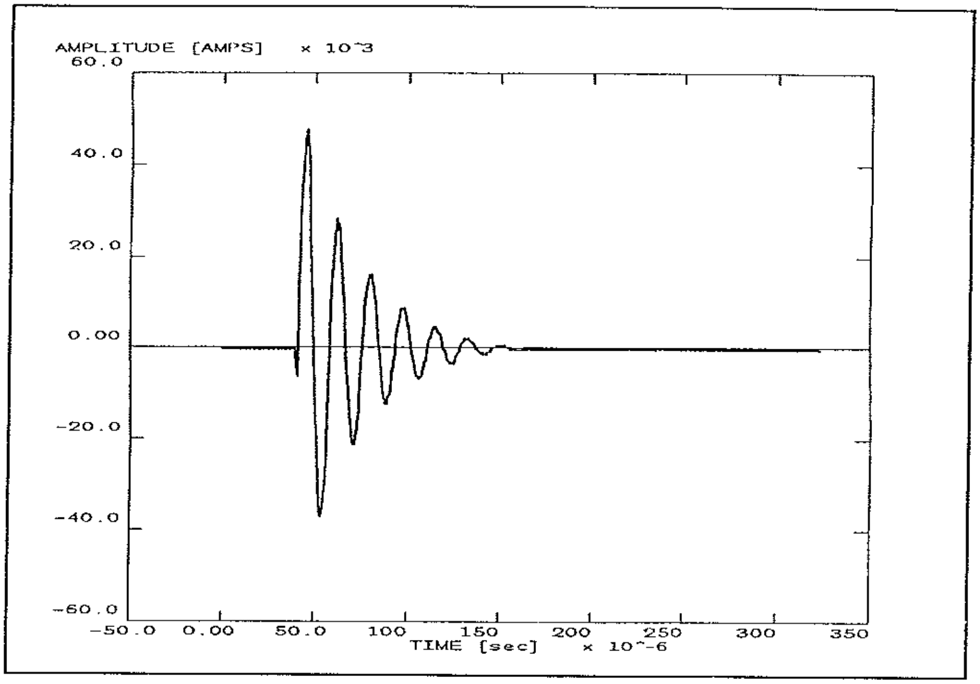

Figure 6. Expanded View of Injected Lightning Pulse in the Time Domain

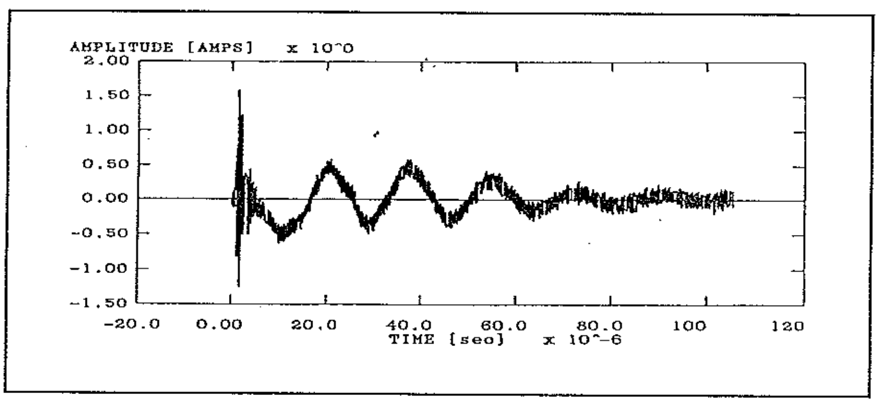

Figure 7. Typical Measured Time-Domain Lightning Response Used For Re-Injection

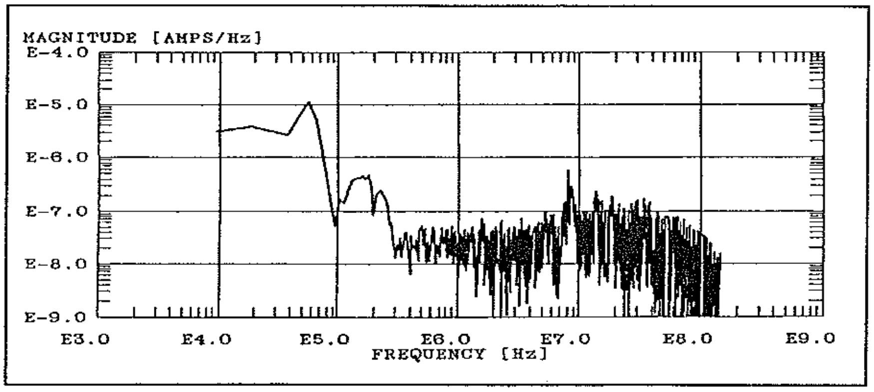

Figure 8. Typical Measured Frequency-Domain Lightning Response Used For Re-Injection

For EMP, the double-exponential waveform is radiated at the system under test by placing the aircraft directly under a horizontally polarized antenna. A ground plane is located below the vehicle to create the condition of a parallel plate.

Aircraft are instrumented during the EMP test. The current probe sensors are positioned near the cable connector on all cable bundles under test to measure the induced transient current pulse. In some cases, a current probe can also be positioned to measure the induced pin current on an individual wire.

For lightning, the various waveforms are injected directly to the aircraft structure at some reduced level. The return path for the current consists of a coaxial type structure built around the vehicle. This structure is necessary to create the condition of directional current flow with a uniform current return path. Any constrained return current path would distort measurements due to the path's generated magnetic field.

In lightning tests, current probes are positioned around cable bundles similar to EMP tests. However, since the frequency range of the lightning induced pulse is lower than the EMP pulse, and since the low frequency current component of lightning is considerably higher, a different set of sensor probes are used. One potential area of further investigation could be the development of broadband sensors capable of being used for both EMP and lightning induced measurements.

ESD system testing is straight forward, and does not require aircraft instrumentation or measurements. It involves two simple pass/fail tests for ordnance initiation. The ESD simulator is brought physically close to an ordnance device installed on the aircraft and the pulse is injected directly. Margin determination is not the intent of the test. Therefore, the possibility for test unification is possible only as the result of a new instrumented-type ESD test at the system level.

During lightning testing, the vehicle is instrumented to measure the resultant transient appearing at the same location where the ESD transient would appear. The measured and then extrapolated lightning transient could be compared and combined with the ESD transient such that the final re-injected waveform would be a single worse case transient.

3. CONFIGURATION MATRIX DEVELOPMENT

A full configuration matrix for all transient tests is shown in Table 1. Notice that natural test reduction groupings are not obvious except as related to each environment. The groupings that appear possible are each of the EMP tests and the lightning T02, T03, and T05 tests. Since these tests are applied differently, conducted verses radiated, the point at which a test reduction might be applied is not readily apparent. A further reduction of the configuration matrix to address only Navy aircraft test methods is shown in Table 2.

4. CONFIGURATION MATRIX CONCLUSIONS

Few conclusions can be drawn regarding the ultimate success of a test reduction effort based on test methodology. What this implies is that it would be difficult to identify an eventual test reduction at the system level, except for scheduling factors. A possible scheduling reduction could relate to performing lightning testing immediately after EMP testing, taking advantage of a potential overlap in sensor instrumentation.

Table 1. Full Transient Test Configuration

SYSTEM ENVIRONMENT	POSITION OF VEHICLE OR SIMULATOR	METHOD (PRIMARY) OR WAVEFORM DESIGNATOR	USUAL TEST WAVEFORM	NORMALLY INSTRUMENTED TEST	REINJECTED AT BOX LEVEL	EXTRAPOLATION DIFFICULTY/ PROBLEMS	TIME DURATION		PEAK AMPLITUDE	FREQUENCY RANGE	POSSIBILITY FOR TEST REDUCTION
							t_r	t_f			
*EMP HPD**	PARALLEL (RELATED TO ANTENNA)	RS	DOUBLE EXPONENTIAL	Y	Y**	NO	7.5 ns	300 ns TO 50%	53 kV/M	10 k - 300 M	DIRECT DRIVE BOX LEVEL
*EMP HPD**	PERPENDICULAR	RS	DOUBLE EXPONENTIAL	Y	Y**	NO	7.5 ns	300 ns TO 50%	53 kV/M	10 k - 300 M	DIRECT DRIVE BOX LEVEL
*EMP HPD**	NOSE ON	RS	DOUBLE EXPONENTIAL	Y	Y**	NO	10 ns	70 ns TO 50%	48 kV/M	10 k - 300 M	DIRECT DRIVE BOX LEVEL
*EMP HPD**	WING ON	RS	DOUBLE EXPONENTIAL	Y	Y**	NO	10 ns	70 ns TO 50%	48 kV/M	10 k - 300 M	DIRECT DRIVE BOX LEVEL
LIGHTNING TO 1	ATTACHMENT POINT/PUNCTURE (ALL TESTS NOSE ON)	CS A (VOLTAGE) D (VOLTAGE)	CRITICALLY DAMPED SINE OR DAMPED SINE	N	N	N/A	1000 kV/µs 50-250 µs	N/A	NA BREAKDOWN		
LIGHTNING TO 2 & TO 3	DIRECT STRUCT. EFFECTS VAPOR IGNITION	CS A-D (CURRENT)	CDS OR DS	Y	Y (SEE TO 5)	LLCW - YES CDS - NO DS-SOME	A .... B .... C .... D	500 µs .... 5 ms ...... .25 - sec- 500 µs	200 kA 2 kA 200 - 800 A 100 kA	0-20 M	DIRECT DRIVE BOX LEVEL WITH (1) OR PARTS OF (1)
LIGHTNING TO 4	CORONA/STREAMERS (USE WAND)	CS B (VOLTAGE)	DS	N	N	N/A	1.2 µs (CREST)	50 µs (50%)			
LIGHTNING TO 5	INDIRECT EFFECTS	CS E (CURRENT)	DS	Y	Y	LLCW - YES CDS - NO DS-SOME	25 kA/µs		50 kA	0-50 M	CAN BE COMBINED AS PART OF TO 2 (A ORD)
ESD HUMAN BODY	DIRECT INJECTION AT FUSE	CS (CAPACITIVE DISCHARGE)	CDS	N***	N	PASS/FAIL	-150 ns	-150 ns	25 kV	10 k - 100 M	3) WITH WAVEFORM CONVOLUTION 4) WITH INSTRUMENTED TEST
ESD AIR REPLENISHMENT	DIRECT INJECTION AT FUSE	CS (CAPACITIVE DISCHARGE)	CDS	N***	N	PASS/FAIL			300 kV	10 k - 100 M	3) MAYBE WAVEFORM CONVOLUTION 4) WITH INSTRUMENTED TEST

* Instumented - Now power (Inducted Transient Measured)
Uninstrumented - Powered Up (Anomonolies Measured)
HPD - Horizontally Polarized Dipole

** Currently Used Maximum Peak from all Tests (Worse Case) for Rejection
*** Could Be Instumented but Usually Just Pass/Fail
VPD - Vertically Polarized Dipole

Table 2. Reduced Test Configurations

Test	Vehicle Position or Test Type	Method	Waveform Used	Instrumented for Box Level Re-Injection	Extrapolation Difficulty	Significant Frequency	Test Reduction Potential
*EMP RS05 - HPD	Parallel to Antenna	RS	Double Exponential	Yes	No	10 kHz - 300 MHz	Direct Drive Box Level
*EMP RS05 - HPD	Perpendicular to Antenna	RS	Double Exponential	Yes	No	10 kHz - 300 MHz	Direct Drive Box Level
*EMP RS05 - VPD	Nose On	RS	Double Exponential	Yes	No	10 kHz - 300 MHz	Direct Drive Box Level
*EMP RS05 - VPD	Wing On	RS	Double Exponential	Yes	No	10 kHz - 300 MHz	Direct Drive Box Level
Lightning - T02	Direct Effects	CS	Critically Damped Sine (CDS) Waveform A	Yes	No**	0 - 20 MHz	Direct Drive Box Level
Lightning - T03	Vapor Ignition	CS	CDS or DS Waveform A	Camera	No	0 - 20 MHz	No
Lightning - T05	Indirect Effects	CS	DS Waveform E	Yes	No	0 - 50 MHz	Can Be Combined With T02
ESD - Human Body	Direct Fuse Injection	CS	CDS	No***	Pass/Fail	10 kHz - 100 MHz	Would Require New Test Method
ESD - Air Replenishment	Direct Fuse Injection	CS	CDS	No***	Pass/Fail	10 kHz - 100 MHz	Would Require New Test Method

* Test is first performed on an un-instrumented powered aircraft to identify anomalies. The aircraft is then instrumented and unpowered to measure induced transients.

** Depends on waveform used. Low-level continuous wave (LLCW) involves significant data extrapolation risk. Damped sine (DS) involves some extrapolation risk. Critically-damped sine (CDS) involves very little data extrapolation risk.

*** Testing is un-instrumented with a pass/fail indication.

Since measurement sensors used for instrumented EMP and lightning tests are similar, it is possible that the vehicle could be moved directly from the EMP site to the lightning site without detaching any measurement instrumentation, then a single re-injection test series could be performed for both EMP and lightning while the vehicle is configured for lightning tests. At the box level, the coaxial return path around the vehicle would have little effect on re-injected signals incorporating both the measured EMP and lightning response.

Another test combination possibility is both of the ESD tests and the lightning TO5 test. In this case, ESD tests are not instrumented currently. However, looking at the entire transient test concept, an effective way to reduce all testing might be to redefine specific test constraints such as those applied for ESD. Some flexibility in how specifications are applied, especially when dealing with multiple environments, might lead to a more effective overall transient test program.

APPENDIX E. PARAMETRIC BREAKDOWN OF TRANSIENT WAVEFORMS

This section breaks the previous waveforms for each transient test into basic parameters for direct comparisons and manipulations. It describes what norms are, how they apply to transient phenomena, and which norms might be useful to this study. The possible formation of composite waveforms from multiple test data and using norm information to evaluate the accuracy of the bounding is also described. Figure 1 indicates the portion of the study covered by this Appendix.

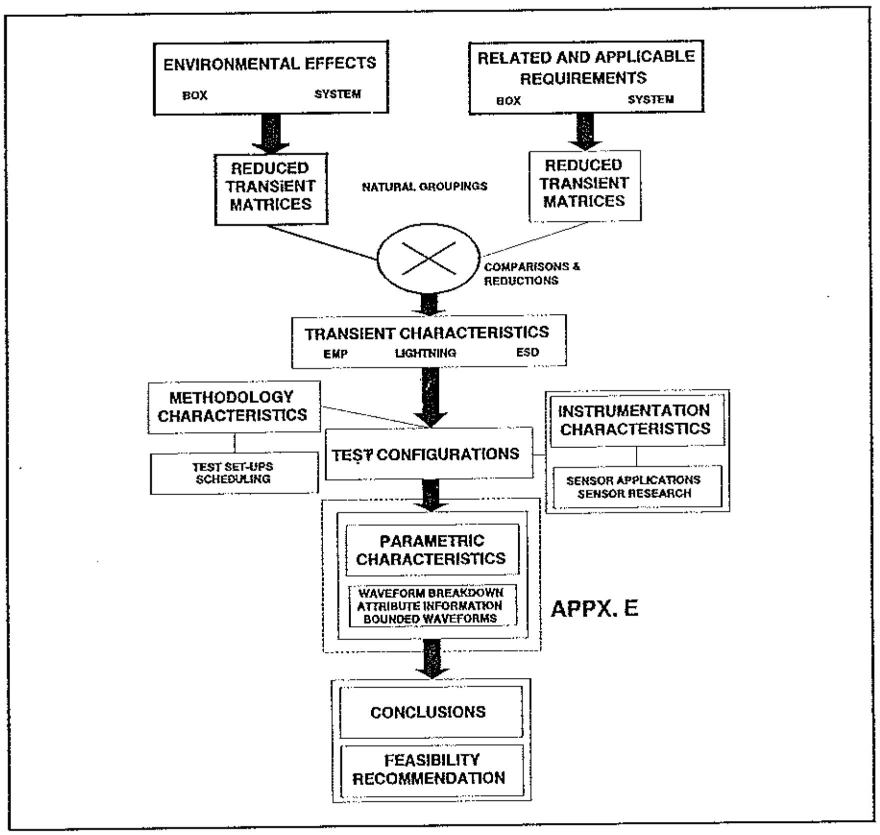

Figure 1. Flow of this Study Section

1. SPECIFYING WAVEFORMS IN TERMS OF NORM ATTRIBUTES

The waveform characteristics represented by various test combinations can be specified in terms of norms. Norms are scaler quantities which characterize in simplified parameters features of a complicated waveform. They are extremely helpful quantities when evaluating the specific components of a particular waveform that interacts with other systems or devices.

Although all transient environments are comparable in terms of norms, such a comparison would have little value in instrumented aircraft testing. However, at the box level, norms assist in direct comparisons.

The full lightning environment is not applied to an aircraft at the same time during testing. Several tests are necessary, each designed to emphasize one or more characteristics of the overall lightning waveform. This technique allows testing to demonstrate overall hardness based on measured effects from the various waveform parameters. Table 1 shows norms associated with the MIL-STD-1795A lightning waveforms.

The use of norms to study and analyze EMP waveforms was first proposed by Carl Baum[1] in 1983, and has since gained acceptance by the EMP community. Norm attributes available for describing the pulsed current injection test waveforms are peak absolute amplitude, peak absolute derivative, peak absolute impulse, rectified impulse, and root action integral. These values are determined by measuring the amplitude, rise time, and other waveform characteristics in the time domain. Mathematically, the standard norm attributes can be expressed as shown in equations 1 through 5.

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1 Baum, C., Black Box Bounds, Interaction Note 429, May 1983.

Table 1. Lightning Waveform Parameters Breakdown

Parameter	Severe Stroke (Component A)	Inter. Current (Component B)	Continuing Current (Component C)	Restrike (Component D)	Multi-Stroke (1/2 Component D)	Multi-Burst
$I_o(A)$	218,810	11,300	400	109,405	54,703	10,572
$\alpha(s^{-1})$	11,354	700	N/A	22,708	22,708	187,191
$\beta(s^{-1})$	647,265	2,000	N/A	1,294,530	1,294,530	19,105,100
i_{peak}	200 KA	4,173 A	400 A	100 KA	50 KA	10 KA
$(di/dt$ max) (A/s)	1.4 x 1011 @ t = 0+ sec	N/A	N/A	1.4×10^{11}	0.7×10^{11}	2×10^{11}
di/dt (A/s)	1.0×10^{11} @ t = 0.5 us	N/A	N/A	1.0×10^{11} @ t = 0.25 us	0.5×10^{11} @ t = 0.25 us	N/A
(A^2s) Action Integral	2.0×10^6	N/A	N/A	0.25×10^6	0.0625×10^6	N/A

$$| f_{(t)} |_{max}$$

(1) Peak Absolute Amplitude

$$\left| \frac{df_{(t)}}{dt} \right|_{max}$$

(2) Peak Absolute Derivative

$$\left| \int_0^t f_{(x)} dx \right|_{max}$$

(3) Peak Absolute Impulse

$$\int_0^\infty |f_{(x)}| \, dx$$

(4) Rectified Pulse

$$\sqrt{\int_0^\infty [f_{(x)}]^2 \, dx}$$

(5) Root Action Integral

Subsequent research by Beilfuss and Gray[2] found that the standard set of EMP waveform norms do not possess the sensitivity needed to be used in direct-drive source selection techniques when applied only to the source waveform. However, their research did indicate that a voltage integral waveform developed from the open circuit voltage waveform and the direct-drive waveform could be integrated numerically producing an acceptable waveform for re-injection. Other researchers[3,4,5] have looked at various aspects of the problem of developing composite waveforms with varying degrees of robustness.

Table 2 lists some norms for both radiated RS05 and box level direct drive transient testing. The problem with using EMP norms based on the specification documents is that they do not correspond to the actual measured data. Lightning tests are based on simulating various parameters of the theoretical strike, while EMP radiated tests are performed using the entire specified waveform. Conducted EMP tests are based on a prediction at the box level, not actual measured results. Therefore, although the actual numbers in Tables 1 and 2 cannot be compared directly, norms appear to be the level at which direct comparisons between the various transient tests are possible.

By using norm attributes to evaluate a waveform derived from various measured waveforms, it may be possible that an adequate composite waveform for subsequent testing might be developed. Based on this initial evaluation, at least at the box re-

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2 Beilfuss, J. and Gray, R., Source Selection Techniques for EMP Direct Drive Simulation, IEEE 1990 Symposium on EMC, Session 3C, Atlanta.

3 Lee, L., Tits, A., and Fan, M., Robustness Under Uncertainty with Phase Information, Proceedings of the 28th IEEE Conference on Decision and Control, October 1989, Tampa. (CH2642-7/89/000-2315)

4 Rolin, Y., Pintelon, R., and Schoukens, J., Amplitude-Only versus Amplitude-Phase Estimation, IEEE Transactions on Instrumentation and Measurement, Vol. 39, No. 6, December 1990. (0018-9456/90/1200-0818)

5 Mikhael, W., and Spanias, A., A Least-Squares Pole-Zero Algorithm in the Frequency and Walsh Domains with Applications to Speech Representation, IEEE Transactions on CAS, 1990. (CH2868-8/90/0000-1331)

Table 2. Relevant EMP Waveform Parameters Breakdown

Parameter	Source	Value
$E_o(t)$	Radiated	5.25 x 10^4 v/m
$\alpha(s^{-1})$	Radiated	4.0 x 10^6/sec
$\beta(s^{-1})$	Radiated	4.8 x 10^8/sec
$I_o(t)$	Conducted	10 amps
i_{peak}	Conducted	10.25 amps

injection level, it was determined a subsequent test reduction is possible. Note that a composite waveform which includes all E^3 must be developed carefully to insure tight, accurate bounds. If one is not careful, they could create a bounding waveform that could be considered extreme worse case.

2. BOUNDING COMPOSITE WAVEFORMS

Depending on antenna orientation and test configuration, each EMP test point has several measurement records. This section addresses combining multiple transient response data into a single composite test point stress waveform. The composite waveform, containing all relevant information and termed the "Stress Envelope", would replace the current approach for inductively coupled direct-drive testing. The basic technique is shown in Figure 2.

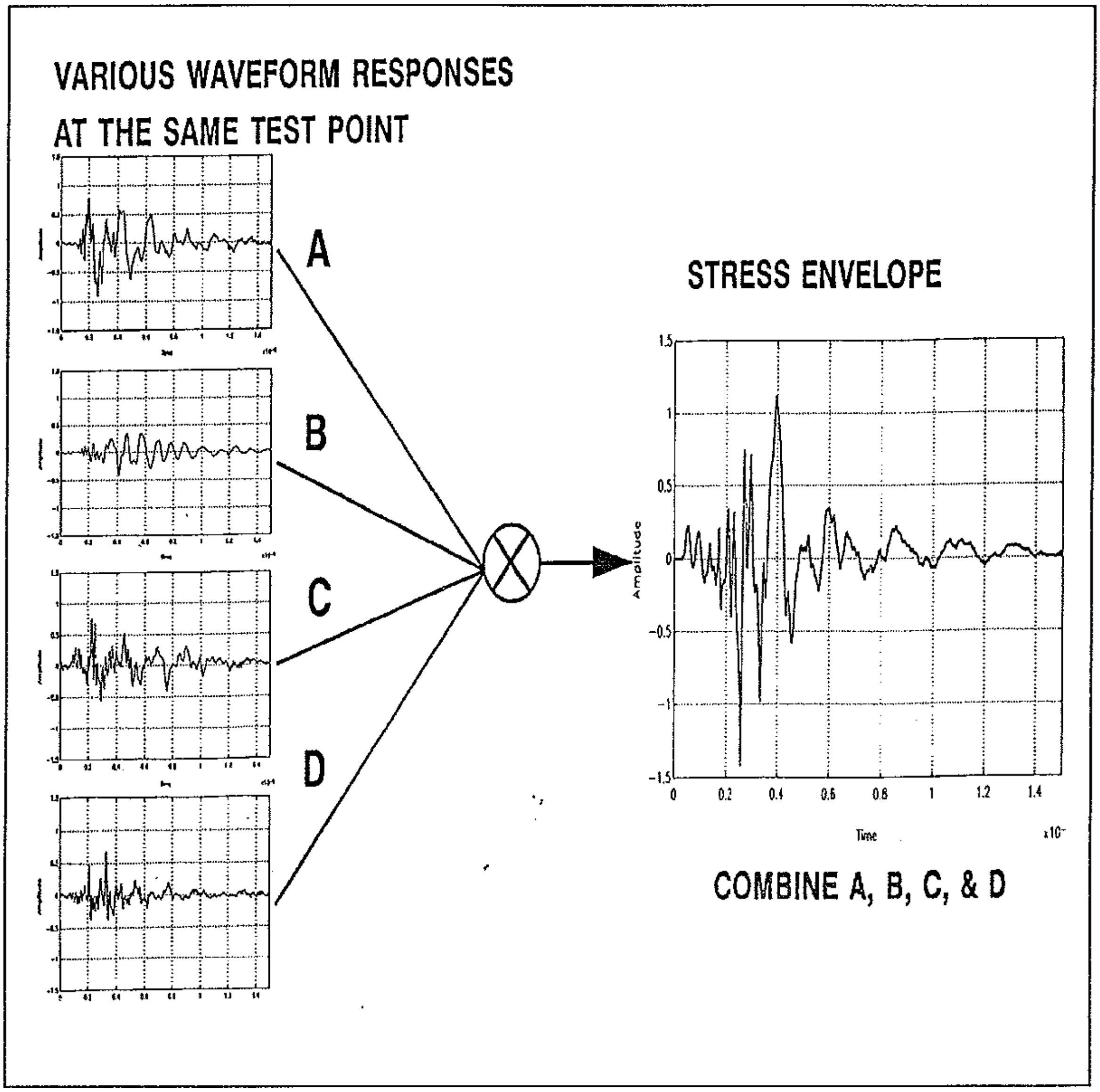

Figure 2. Composite Waveform Development

2.1 Methods for Developing Envelopes

Although a number of methods are available for developing envelopes, autoregression and damped-sine characterization have been considered in EMP research[6].

Two autoregression techniques are under investigation by the Navy[6] One, the autoregression approach (AR), uses weighted averages. The second, autoregression moving averages (ARMA) merges AR with a moving average technique. Either method progressively fits each measured test waveform into a single polynomial equation. The methods further reduce the multiple waveform polynomials into a single envelope.

Damped-sine characterization (DSC) is a non-linear technique of characterizing a test measurement as the sum of a small number of individual damped-sine waveforms. The DSC decomposes a waveform into multiple poles. The resulting poles from all data are placed in a table and reduced by eliminating non-contributing smaller poles located close to larger poles. A single envelope is then constructed from the poles that remain.

It is possible that a single waveform could be constructed from multiple measurements during both lightning and EMP transient testing in various test configurations at the system level. This final, bounded, worse case waveform could then be re-injected at the box level to produce an acceptable result. This approach would be similar to the MIL-STD-461C approach described in Appendix B.

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