NEM 1982 RECORD

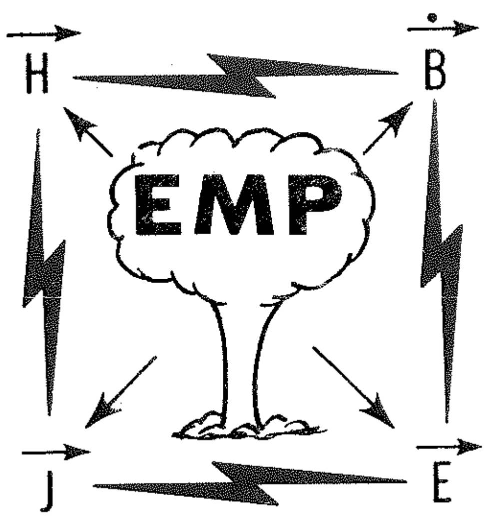
ABSTRACTS OF TECHNICAL PAPERS

Nuclear EMP Meeting

May 24-28, 1982

University of New Mexico

Albuquerque, New Mexico



In Conjunction With:

International IEEE Antennas and Propogation Society Symposium

National Radio Science Meeting

TECHNICAL PROGRAM SUMMARY
MAY 1982 JOINT URSI (B, E, F)/APS/NEM MEETING
UNIVERSITY OF NEW MEXICO, ALBUQUERQUE

LOCATION	MONDAY, MAY 24		TUESDAY, MAY 25		WEDNESDAY, MAY 26		THURSDAY, MAY 27		FRIDAY, MAY 28
	8:30 - 12:00	1:30 - 5:00	8:30 - 12:00	1:30 - 5:00	8:30 - 12:00	1:30 - 5:00	8:30 - 12:00	1:30 - 5:00	8:30 - 12:00
North Ballroom, Student Union Bldg.	AP-1 Scattering	AP-4 Components	AP-9 Antenna Measurements	AP-12 Wave Propagation		AP-15 Antennas in Systems AP-16 Coherence and Interference	AP-19 Numerical Methods for Scattering	AP-22 Analytical and Numerical Methods for Antennas	AP-25 Inverse Scattering & EM AP-26 Remote Sensing
Central Ballroom, Student Union Bldg.	AP-2 Tolerances & Distortions in Antenna Systems	AP-5 Lens Antennas	AP-10 Shaped Reflector Antennas	AP-13 Multiple-Beam Satellite Antennas		AP-17 Phased Arrays	AP-20 Arrays and Array Elements	AP-23 Reflector Antenna Computational Techniques	AP-27 Low Sidelobe and Adaptive Arrays
South Ballroom, Student Union Bldg.	AP-3 Microstrip Antennas I	AP-6 Microstrip Antennas II	AP-11 Microstrip Antennas III	AP-14 Helical and Circular Antennas	PLENARY SESSION	AP-18 Dichroic Surfaces and Reflector Antennas	AP-21 Small and Compact Antennas	AP-24 Microwave and Millimeter Wave Antennas	AP-28 Multiple-Beam Antennas
Room 103, Education Center	URSI-B-1 Media Interface Effects URSI-B-2 Aperture Theory	URSI-B-4 AP-7 Deschamps Session	URSI-B-5 Electromagnetic Theory	URSI-B-7 High Frequency Techniques (GTD)		URSI-B-9 Scattering	URSI-B-12 Inverse Scattering I	URSI-B-14 Inverse Scattering II	URSI-B-15 Antenna Theory II (Microstrip)
Room 101, Education Center	URSI-B-3 Guided Waves		URSI-B-6 Propagation Theory	URSI-B-8 Numerical Methods	STUDENT UNION BALLROOM	URSI-B-10 Antenna Theory I	URSI-B-13 Transients and SEM		
Room 104, Education Center	NEM-1 Cable and Enclosure Shielding	NEM-4 Multi-Conductor Cable Responses	NEM-6 Numerical Techniques	NEM-9 Source Region Analysis NEM-10 System Level Testing		URSI-B-11 URSI-E-5 NEM-12 Scien. Basis for Noise & Interference Control	NEM-14 Interaction Analysis	NEM-16 System Interaction	NEM-18 Nonlinear Breakdown Phenomena
Kiva Auditorium	NEM-2 EMP Hardness Assessment	NEM-5 Failure Thresholds	NEM-7 Source-Region Interaction	NEM-11 Instrumentation for EMP Measurements		NEM-13 EMP Simulation Technology I	NEM-15 EMP Simulation Technology II	NEM-17 System Hardening Technology	NEM-19 Scale Model Measurements & Extrapolation NEM-20 Hardness Assurance Monitoring Systems
Room 204, Education Center	URSI-E-1 NEM-3 Lightning I	AP-8 Tropospheric Propagation URSI-E-2 Shielding	URSI-E-3 NEM-8 Lightning II	URSI-E-4 Noise Measurements and Interference		URSI-F-1 Remote Sensing	URSI-F-2 Propagation I	URSI-F-3 Propagation II	URSI-F-4 Propagation III

WELCOME
TO
ALBUQUERQUE

On behalf of the IEEE Antennas and Propagation Society, the U. S. National Committee of the International Union of Radio Science, and the Permanent NEM Committee, I would like to welcome all of the conference participants to the University of New Mexico for what is expected to be an outstanding conference.

I would like to thank the University of New Mexico for being a very capable and gracious host. Special thanks and recognition is also due to the conference committee which was divided into several major parts. Besides the arrangements committee there were three technical committees, one for each of the sponsoring groups. The Albuquerque Convention and Visitors Bureau provided considerable assistance with the housing as well as other matters.

There is plenty for everyone to do at this conference. There are roughly 500 papers to choose among; there is a very interesting plenary session on Wednesday morning; there are business meetings of various groups and various social events and tours. Of course there is also the banquet Wednesday evening. Consult your program and watch the registration area for bulletins.

I wish all of you a most productive conference and one that you will wish to remember in future years.

Dr. Carl E. Baum
Conference Chairman

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U.S. National Committee of the International Union of Radio Science (USNC/URSI)--
Commission B: Field and Waves
Commission E: Interference Environment
Commission F: Wave Phenomena in Non-Ionized Media

Permanent NEM Committee--

In cooperation with the following government agencies:

Harry Diamond Laboratories
Naval Surface Weapons Center
Air Force Weapons Laboratory
Defense Nuclear Agency

and in cooperation with

The Electromagnetics Society

HOST: The University of New Mexico

PLENARY SESSION
WEDNESDAY 8:30-12:00
STUDENT UNION BALLROOM

Chairman: K. S. Kunz
Kunz Associates, Inc.
Albuquerque, NM

SESSION NEM-1
MONDAY 8:30-11:40
EDUCATION CENTER, Room 104

CABLE AND ENCLOSURE SHIELDING

Chairman: W. S. Kehrer
Air Force Weapons Laboratory
Kirtland AFB, NM

SESSION NEM-2
MONDAY 8:30-12:00
KIVA AUDITORIUM

EMP HARDNESS ASSESSMENT

Chairman: C. Ashley
Air Force Weapons Laboratory
Kirtland AFB, NM

SESSION URSI-E-1/NEM 3 LIGHTNING I
MONDAY 8:30-10:10
EDUCATION CENTER, Room 204

Chairman: C. Moore
New Mexico Institute of Technology
Socorro, NM

SESSION NEM-4 MULTI-CONDUCTOR CABLE RESPONSES
MONDAY 1:30-5:00
EDUCATION CENTER, Room 104

Chairman: A. Agrawal
The Dikewood Corporation
Albuquerque, NM

SESSION NEM-5
MONDAY 1:30-5:00
KIVA AUDITORIUM

FAILURE THRESHOLDS: TESTING AND ANALYSIS

Chairman: K. R. Enkenhus
Naval Surface Weapons Center
Silver Springs, MD

SESSION NEM-6
TUESDAY 8:30-12:20
EDUCATION CENTER, Room 104

NUMERICAL TECHNIQUES

Chairman: R. Oats
Atomic Weapons Research Establishment
Aldermaston, UK

SESSION NEM-7
TUESDAY 8:30-12:20
KIVA AUDITORIUM

SOURCE REGION INTERACTION

Chairman: L. F. Libelo
Harry Diamond Laboratories
Adelphi, MD

SESSION URSI-E-3/NEM-8 LIGHTNING II
TUESDAY 8:30-11:00
EDUCATION CENTER, Room 204

Chairman: K. Zeisel
McDonnell Aircraft Company
St. Louis, MO

SESSION NEM-9 SOURCE REGION ANALYSIS
TUESDAY 1:30-2:50
EDUCATION CENTER, Room 104

Chairman: Madame F. Amaurdic du Chaffaut
CEA
Paris, France

SESSION NEM-10
TUESDAY 3:20-5:20
EDUCATION CENTER, Room 104

SYSTEM LEVEL TESTING

Chairman: L. Marin
The Dikewood Corporation
Santa Monica, CA

SESSION NEM-11 INSTRUMENTATION FOR EMP MEASUREMENTS
TUESDAY 1:30-4:40
KIVA AUDITORIUM

Chairman: C. Giles
EG&G, Inc.
Albuquerque, NM

SESSION URSI-E-5/URSI-B-11/NEM-12
WEDNESDAY 1:30-5:00
EDUCATION CENTER, Room 104

SCIENTIFIC BASIS FOR NOISE AND INTERFERENCE CONTROL

Chairman: E. Vance
SRI International
Menlo Park, CA

SESSION NEM-13 EMP SIMULATION TECHNOLOGY I
WEDNESDAY 1:30-5:00
KIVA AUDITORIUM

Chairman: T. Karlsson
FOA
Linköping, Sweden

SESSION NEM-14
THURSDAY 8:30-12:00
EDUCATION CENTER, Room 104

INTERACTION ANALYSIS

Chairman: J. Bertuchoz
NC Laboratory
Spiez, Switzerland

SESSION NEM-15 EMP SIMULATION TECHNOLOGY II
THURSDAY 8:30-12:00
KIVA AUDITORIUM

Chairman: P.A.A. Sevat
TNO
The Hague, Netherlands

SESSION NEM-16 SYSTEM INTERACTION
THURSDAY 1:30-5:00
EDUCATION CENTER, Room 104

Chairman: R. Sturm
WWDbW
Munster, F.R. Germany

SESSION NEM-17
THURSDAY 1:30-5:00
KIVA AUDITORIUM

SYSTEM HARDENING TECHNOLOGY

Chairman: J. Gut
Research Institute for Protective Construction
Zurich, Switzerland

SESSION NEM-18
FRIDAY 8:30-12:00
EDUCATION CENTER, Room 104

NONLINEAR BREAKDOWN PHENOMENA IN SOILS AND OTHER MATERIALS

Chairman: R. N. Carlile
University of Arizona
Tucson, AZ

SESSION NEM-19
FRIDAY 8:30-10:10
KIVA AUDITORIUM

SCALE MODEL MEASUREMENTS AND EXTRAPOLATION TECHNIQUES

Chairman: J. P. Castillo
Air Force Weapons Laboratory
Kirtland AFB, NM

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SESSION NEM-20
FRIDAY 10:40-12:20
KIVA AUDITORIUM

THEORY AND IMPLEMENTATION OF HARDNESS ASSURANCE MONITORING SYSTEM

Chairman: W. Prather
Air Force Weapons Laboratory
Kirtland AFB, NM

THE MAYPOLE (HOOP/COLUMN) ANTENNA DEVELOPMENT PROGRAM

by

Thomas G. Campbell and David H. Butler

Langley Research Center

INTRODUCTION

The Maypole hoop/column antenna concept is a deployable space frame that has the potential capability of providing several different reflector surface contour designs from the same basic configuration. Therefore, this concept was selected for development to a feasibility level by the Langley Research Center (LaRC) during the Advanced Application Flight Experiment (AAFE) Program. But now, more detailed design and analytical activities (coupled with hardware verification tests) are underway through the Large Space Antenna (LSA) Program at LaRC. The hoop/column point deployed design configuration is shown in Figure 1 and the stowed geometry configuration is shown in Figure 2. Since the applicability of the hoop/column concept with respect to the antenna focus missions is of utmost concern, the results of the mission scenario activity strongly influenced the selection of the baseline configuration--the point design for the LSA Program. Basically, the communication mission scenario was adjudged to contain a significant number of technology drivers; so, the baseline configuration for the hoop/column was selected on that basis. Therefore, it was imperative that the hoop/column antenna be configured so that the requirements associated with the communication mission (beams using offset feed reflectors) would be addressed. Hence, a significant difference between the LSA effort and the previous AAFE study is in the antenna feed configuration that is required for the hoop/column reflector.

During the AAFE study, axisymmetric feed configuration (F/D < 1) were used; but emphasis is now placed on asymmetric feed configurations. So a multiple aperture concept (F/D > 1) using offset feed configurations was introduced using the hoop/column design. The multiple aperture approach has led to a quad aperture point design for subsequent hardware development. The quad aperture concept is generated by defining a separate reflector surface in each quadrant of the basic antenna surface. This concept appears to be very promising as several offset fed apertures could be provided within the same antenna structure. The focal point for each quadrant reflector is totally offset so that the feed system does not block the aperture. With this multiple aperture approach, the area now available for the feed array elements has been increased significantly. To meet multiple beam requirements, 55 beams could illuminate each quad reflector to produce a total of 220 beams from the entire system. Each feed array will be attached to the central column and beam interleaving is adjusted by translating the feed array in two dimensions. This approach should effectively scan the beams and fix the beam-to-beam crossover points at the desired levels. The total structural size for the offset geometry is the same for the symmetrical configuration so that F/D for the offset reflector is essentially doubled.

The use of the quad aperture hoop/column antenna configuratior could also require innovative mesh designs for the reflective surfaces. For example, multiple meshes will be required throughout the quad reflector for the following reasons: first, an open mesh (transparent at the operating wavelength) will be used on the main portion of the reflector but outside the respective illuminated regions. This would allow side lobe energy to leak through the outside region of the reflector. Secondly, the reflector mesh system could accommodate dual frequency operation (C-band and Ku-band) by using frequency selective surface (FSS) techniques, the FSS material in each quad aperture would allow for the wavelength differences (2.5) and produce equivalent beamwidths at each frequency.

Therefore, it can be seen that the quad aperture hoop/column concept is more complex than a symmetrical configuration and, indeed, more challenging from an antenna design standpoint. Also, the technology that is developed through the LSA Program should be more beneficial. The critical parameters selected for the 100-meter point design quad aperture configuration are listed below:

- 100-meter diameter parent reflector,
- Quad offset apertures--40.6 meters, in diameter each,
- F/D = 1.53,
- Focal length (single offset)--62.12 meters,
- Frequency for the point design--2.0 GHz
- Half power beam width--0.256°,
- 220 beams, 55 beams/aperture,
- Surface accuracy--$\lambda/20$,
- Beam to beam isolation--30 dB,
- Gain--55.4 dB, and
- Point accuracy--0.03°

CONCEPT DEVELOPMENT PROGRAM

The Hoop/Column Development Program at LaRC will complete the design and conduct design verification tests to prove that the multiple aperture concept can provide efficient multiple beam performance characteristics. After completing the numerous LSA activities, it will then be possible to evaluate this concept through meaningful trade-off studies. Recognizing the fact that smaller deployable designs do not adequately identify problems associated with large antennas, the technology efforts are focused on the following issues:

- Development and demonstration of hoop/column reflector technology to satisfy focus mission requirements;

- Verfication of the analytical technique for predicting reflector performance,
- Development and verification of scaling relationships that allow extrapolation of performance to a wide range of antenna sizes,
- Development and verification of design analytical and control methods for reflector surface adjustment techniques,
- Development and demonstration of measurement systems to allow orbital evaluation of the reflector contour, including integrated demonstration of these measurement systems with the reflector,
- A verified parametric cost model for each large antenna system, and
- Verified techniques and procedures for the manufacture, assembly, and testing of large antenna systems.

EXPERIMENT MODELS

Efforts with the concept development program area will: (1) provide hoop/column scaled hardware models which satisfy the focus mission configuration requirements, and (2) identify critical hoop/column components. This will be accomplished by building full-scale components and subscale engineering verification models where necessary. The verification models will:

- Establish fabrication and assembly procedures for large size, cable supported, mesh reflectors,
- Demonstrate that large scale mesh reflectors can be built to a prescribed curvature within acceptable tolerances,
- Establish the surface shape to the desired contour and establish if inflight adjustments of the surface are necessary,
- Determine the compatibility of an engineering in-flight surface accuracy measurement system (SAMS) with the hoop/column design,
- Compare experimental results of surface setting and adjusting on the model with analytical predictions of surface accuracy and surface improvements to cable adjustment,
- Establish ground handling procedures for folding the hoop, mesh, cables, and mast into the stowed position,
- Demonstrate the deployment kinematics of the hoop, mesh, cables, and mast during the deployment sequence,
- Measure the surface accuracy of a mesh surface after deployment, and
- Establish the effects of cable blockage on the RF performance of the antenna.

There are three major engineering models planned for the hoop/column technology development program: (1) a 50-meter surface adjustment model, (2) a 15-meter deployment antenna model, and (3) an RF verification model. These models will be developed in accordance with the plan referred to earlier.

CONCLUDING REMARKS

The development of the hoop/column antenna is ongoing. A 4-gore section of a 50-meter diameter reflector has been fabricated and tested. Plans are now underway for the development and tests of the 15-meter diameter kinematic reflector model. The 15-meter model development is planned to be completed in (FY) 1984. The results of the hoop/column development program will provide analysis methods that will be validated using subscale reflector models. The successful conclusion of these activities will provide NASA the capability to conduct meaningful trade-off studies for large space antenna applications. These studies would include risk-assessment, performance prediction (RF and structural) and, antenna costs projections. Also, definition activities for a large antenna flight experiment could then be made using known antenna capabilities.

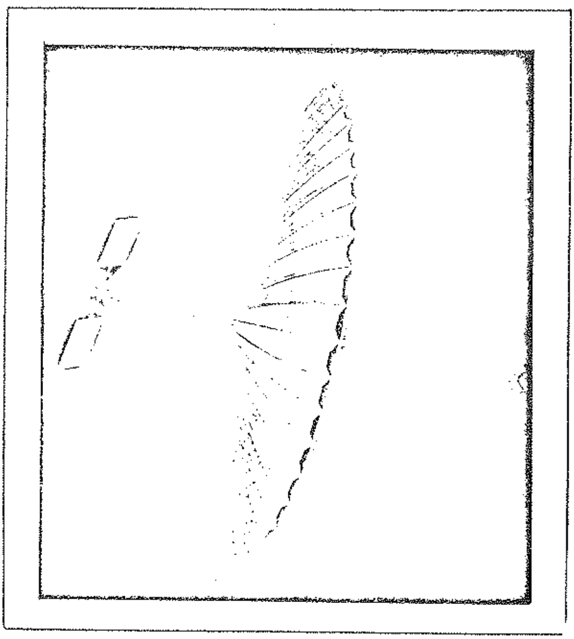

Figure 1. Deployed Configuration of the Maypole Hoop/Column Antenna Concept.

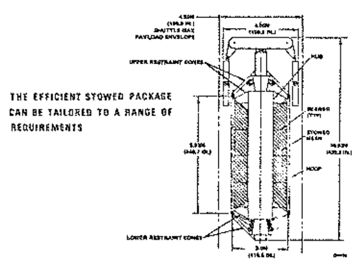

Figure 2. Stowed Configuration of the Maypole Hoop/Column Antenna.

PULSED POWER TECHNOLOGY AT SANDIA NATIONAL LABORATORIES

G. Yonas
Sandia National Laboratories
Albuquerque, NM 87185

Pulsed power in the U.S. has progressed substantially over the last fifteen years based on support from the D.O.D. and D.O.E. for near term defense and long term energy applications. Sandia began its effort with Hermes II which was developed in collaboration with the A.W.R.E. This gamma-ray simulator has been an active part of the D.O.E. weapons effects testing program with 20,000 shots since 1967. An advanced simulator, Hermes III, now under prototype development, will provide improved dose-rate and larger area testing capabilities. Hermes III will encompass many of the developments from the D.O.E. inertial fusion program as embodied in PBFA-I as well as from the A.F.W.L./Sandia multi-stage accelerator technology program, RADLAC.

PBFA-I, a 36 module, 2 MV, 30 TW accelerator began operation in 1980 and is currently being employed to investigate voltage addition and ion diode scaling using magnetically insulated reconnection. PBFA-II, with 36 modules and a 100 TW output, will be configured to allow its use, beginning in 1986, as either an ion accelerator at 10 MV or an imploding foil driver at 30 MA.

RADLAC I has produced a 25 kA, 9 MeV electron beam through post acceleration of a 2 MeV beam by four radial pulse line driven cavities. RADLAC II, now under construction, will allow us to explore the extension of this approach to higher currents and voltages. Other activities include development of repetitive pulse components, low jitter switching, multi-stage and collective ion acceleration, and explosive power supplies with fast opening switches.

With the inception of modular, multi-stage pulseline techniques and methods for voltage or current addition, pulsed power has opened up a new dimension in power concentration. With the inevitable future improvements in compact pulse forming and energy storage, synchronized switching, and breakdown suppression, the opportunities for further application of pulsed power will accelerate.

THE NUCLEAR ELECTROMAGNETIC PULSE PROGRAM: EVOLUTION AND IMPACT ON TECHNOLOGY

Dr. J. Philip Castillo
Air Force Weapons Laboratory/NTYE
Kirtland Air Force Base, New Mexico 87117

This paper will present the evolution of the technical developments in nuclear electromagnetic pulse (EMP) technology and its dependence on and relationship to electromagnetics. This technical area includes the physics of generation of the EMP, the interaction of EMP with objects as well as methods for the simulation of the EMP. General methods for testing and protecting electronic equipment will be discussed.

The EMP program impact on the electromagnetic technology will be presented including instrumentation and theoretical aspects. A history of the EMP technology development will be included.

AIR FORCE HIGH ENERGY LASER PROGRAM

by

JAMES D. DILLOW
AIR FORCE WEAPONS LABORATORY
KIRTLAND AIR FORCE BASE, NEW MEXICO

Abstract

The purpose of this presentation is to describe selected technical aspects of the Air Force Weapons Laboratory's high energy laser program. The presentation is introduced with a film of the Delta experiment, where a drone aircraft was destroyed in the air by a high energy laser. In order to put the technology programs in perspective, a generic high energy laser weapon system is discussed and the Air Force Weapons Laboratory technology program is overviewed.

The technology areas are selected for further description -- devices and beam control. First, the laser devices that are being developed by the Air Force Weapons Laboratory are briefly described. In order to describe the Air Force Weapons Laboratory beam control technology program, a state-of-the-art beam control system is compared to a generic advanced beam control concept. The reliance on adaptive optics in advanced systems is pointed out and two adaptive optics systems being studied by the Air Force Weapons Laboratory are selected for further description.

RECENT OBSERVATIONS WITH THE VLA RADIO TELESCOPE

R. A. PERLEY NATIONAL RADIO ASTRONOMY OBSERVATORY

The VLA (Very Large Array) is the world's most powerful and flexible radio telescope. Situated on a high plain in western New Mexico, the VLA was built by the National Radio Astronomy Observatory, and is designed to provide high quality maps of celestial radio sources. Comprising 27 25- meter parabaloidal reflectors, the instrument provides maps of the sky visible within the antenna primary beam through Fourier inversion of the 351 cross-correlations. It operates in any of four bands, centered roughly near 1.5, 5, 15 and 23 GHz, with a sensitivity of up to 10^{-31} watt m^{-2} Hz^{-1} at the two lower bands, and with a resolution, at 5 GHz, of $\sim 0.3''$. The VLA can operate in a continuum mode, with bandwidths of up to 50 MHz, or in spectral line mode with up to 256 channels with frequency resolution selectable from 12.5 MHz to 400 Hz.

The VLA was dedicated in October, 1980, and since then has been used by astronomers from around the world to map a wide range of astronomical objects. These may be classified in three groups:

A) Solar and Planetary. Maps of the active and quiet sun, and of most of the planets, have now been made.

B) Galactic. Our galaxy contains a very wide assortment of radio emitting objects and regions. Objects observed at the VLA include stars, planetary nebulae, supernova remnants, molecular clouds, the galactic center, HII regions and exotic objects such as SS433.

C) Extragalactic Beyond our galaxy lies inmumerable radio emitting objects, including normal galaxies, Seyfert galaxies, radio galaxies and quasars. These ofter appear very differently in the radio region of the spectrum than do the optical objects, and have been the subject of much VLA observing time.

In the talk, many of the latest observations from these and other astronomical objects will be shown, and the scientific implications briefly discussed.

ELECTROMAGNETIC COUPLING THROUGH CABLE SHIELDS*

Prem N. Setty and John E. Tigner

ELECTROMAGNETIC/RADIATION EFFECTS DIVISION
SCIENCE APPLICATIONS, INC.
1710 Goodridge Drive
McLean, Virginia 22102

It is essential for the System/Design Engineer to have an estimate of the SGEMP/IEMP coupling through cable shields, or the shielding effectiveness, in order to effectively harden the system. What is required is an analysis methodology which, in combination with an experimental determination of the shielding effectiveness of complicated harness configurations, will assist the Design Engineer in verifying the hardness of the system to the threat environment. In this paper, we shall describe such a methodology (LEAK) to determine the shield to core coupled signal for an arbitrary multibranch, multiwire, multimode configuration. This methodology is ideally suited for SGEMP responses (small pulse widths) in long cable harnesses (long propagation times with breakouts).

This methodology serves as an effective tool to:

(1) estimate the shielding effectiveness of a harness configuration in-situ;
(2) assist a Design/System Engineer in choosing optimum cable shield type and parameters to maximize shielding effectiveness;
(3) evaluate alternative harness configuration to minimize shield/core coupled signal;
(4) support the development of a shielding effectiveness test methodology; and
(5) evaluate required shield/core transfer functions to ensure a particular drive mechanism is dominant if that is the design constraint.

Using analytical and empirical relationships for estimating the electromagnetic coupling through shields, we shall compare shielding effectiveness calculations obtained using this methodology to experimental results obtained from the DNA (General Electric cable shielding effectiveness tests) program.

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*Work supported by the DEFENSE NUCLEAR AGENCY under Contract Number DNA001-81-C-0005.

A SIMPLE THEORY FOR UNDERSTANDING THE MAGNETIC FIELD ATTENUATION OF ENCLOSURES

AUTHORS: P. J. Madle
TRW, Inc.
Redondo Beach, CA
and
L. O. Hoeft
The BDM Corporation
Albuquerque, NM

EMP analyses frequently use magnetic field attenuation to specify the performance of enclosures. The magnetic field attenuation is the ratio of the magnetic field inside the enclosure to the surface magnetic field on the exterior of the enclosure. This paper presents a simple theory that is useful for understanding the mechanisms involved in the coupling of magnetic fields into enclosures.

This theory is based on a model of the enclosure that represents the enclosure as a large single turn loop. The enclosure is electrically small (a good approximation up to tens of MHz) therefore currents are everywhere the same. The enclosure is thick enough so that current does not diffuse through the material (a good assumption above 100kHz). The exterior magnetic field or surface current is coupled to the inside by the finite transfer impedance of the joints. The exterior surface current produces a voltage across the joint transfer impedance which in turn produces a current in the interior of the single turn loop and a magnetic field in the interior of the enclosure.

The use of this model results in an analytic expression for the magnetic field attenuation in which the denominator is related to the transfer impedance of the joint and the numerator is related to the size of the enclosure. If the joint is predominately a resistor, the magnetic field attenuation should change at 20dB/decade. If the joint is predominately an aperture, the magnetic field attenuation is frequency independent.

The measured magnetic field attenuation of a wide range of generic enclosures is consistent with this simple theory. It appears to be most useful for interpreting experimental results and making design iterations.

MEASUREMENT OF THE MAGNETIC FIELD REDUCTION PROVIDED BY GENERIC EQUIPMENT CASES AND ENCLOSURES

AUTHORS: L. O. Hoeft, R. J. Karaskiewicz, J. S. Hofstra, and T. J. Andrews
The BDM Corporation, Albuquerque, New Mexico

One measure of the shielding provided by enclosures is the ratio of the magnetic field inside the enclosure divided by the surface magnetic field on the outside of the enclosure. This ratio is defined here as the magnetic field reduction or attenuation.

The magnetic field attenuation of three types of equipment cases and two enclosures was measured for frequencies between 100Hz and 100MHz using several types of TEM cells. The equipment cases included a common aluminum chassis with a simple cover, a pair of deep drawn aluminum boxes attached to each other by a machined flange and a commercially available steel box with an "RFI" gasket. The enclosures included two enclosures approximately 8' x 4' x 2' each divided into four equipment bays and a cable bay across the back. The enclosures differ in their construction, namely, one was made of 1/16" aluminum pop-riveted to aluminum angle while the other was constructed of two layers of 1/32" aluminum separated by ½ plywood (a simulation of honeycomb) inserted into extrusions and fastened with bolts on 4" centers.

Except for the simple chassis box the magnetic field attenuation of the equipment cases was almost directly proportional to frequency throughout the frequency range. The magnetic field attenuation of the chassis box was proportional to frequency from 100 to 10,000Hz, then slowly increased another -15dB in the range of 10kHz to 1MHz and then became frequency independent. The steel case with gasket provided the best magnetic field attenuation (about -90dB at 10MHz). The deep drawn aluminum case provided about -80dB at 10MHz without a gasket.

The magnetic field reduction of the simple enclosure was similar to that of the simple chassis box, -50dB in the 1 to 10MHz range increasing to -58dB at 50MHz. The performance of the more complex enclosure was significantly better With the equipment bay cover simply placed on the enclosure, -40dB of magnetic field reduction was achieved between 500kHz and 100MHz and was -94dB at 10MHz When half of the screws were removed, the magnetic field attenuation decreased by 6dB.

The measured magnetic field attenuation of the generic equipment cases and enclosures was always less than that predicted by plane wave shielding calculations. The measured electromagnetic performance was consistent with a simple theory that considered the finite impedance of a joint as the mechanism for coupling current from the exterior to the interior of the enclosure.

THEORETICAL AND EXPERIMENTAL TRANSFER IMPEDANCE
OF CONCENTRIC LAYERS OF COAXIAL SHIELDING

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Modeling concentric layers of braided shields is an integral part of system hardening technology for EMP. To determine the accuracy of a multiple shield model, the model is compared to measured data. This paper compares theoretical and experimental transfer impedance data for 1, 2 and 3 layers of tubular braided shields, from 1 kHz to 100 MHz using transmission line theory and a quadraxial test fixture. These results suggest an interlayered inductance should be included for any modeling of multiple braid layers even though the different braid layers are in contact many times along their length. This confirms Schelkunoff's total transfer impedance theorem (ref. 1) along with the provisio on including shield to shield inductive reactance.

The measured data also showed that the simplifying high frequency approximations made for total transfer impedance is inadequate to describe multiple layered braided shields since the transfer impedance is found not to be directly proportional to frequency (ref. 2).

1. S. A. Schelkunoff, "The Electromagnetic Theory of Coaxial Transmission Lines and Cylinderical Shields," Bell System Tech. J., Vol. 13, pp. 532-579, October 1934.

2. E. F. Vance, "Coupling to Shielded Cables," Wiley-Interscience, John Wiley and Sons; New York 1978, p. 168.

MEASURED TRANSFER IMPEDANCE OF BRAID AND CONVOLUTED SHIELDS

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There is a wide variety of shield materials for cable bundles however, little measured transfer impedance data exist. This paper will present measured transfer impedance data, from 1 kHz to 100 MHz using a quadraxial test fixture for both braids and a variety of other cable bundle shields including: magnetic and non-magnetic convoluted shields, tape wound aluminum and stainless steel conduits with and without overbraid and metal tapes. The measured transfer impedance for one and six meter length tubular and machine braided shields will also be presented. Such a collective sampling of measured transfer impedance data is not present in the literature.

The measurements show the overbraid reduces the transfer impedance of convolutes and tape wound conduits by a factor of 10 to 100. The transfer impedance of braided shields measured in this study is consistent with the high frequency shielding effectiveness measurements by others (ref. 1). The present measurements extend to 1 kHz and allow comparison with d.c. resistance measurements. The braided shields for 2 and 3 layers of braid show that the simple mutual inductance model (ref. 2) is inadequate to define the performance of these shields, since the high frequency transfer impedance is not proportional to frequency. These measurements suggest the need for a more sophisticated model.

1. E. D. Knowles and L. W. Olsen, "Braided Cable Shielding Effectiveness Study," Boeing Contract No. AF04 (694)-791, 1970.

2. E. F. Vance, "Coupling to Shield Cables," Wiley Interscience, John Wiley and Sons; New York 1978, p. 168.

TRANSFER IMPEDANCE FOR ONE AND TWO LAYER SHIELDING TOPOLOGIES WITH BACKSHELLS

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Almost all cable assemblies have the shield terminated to a backshell and connector. An optimum shield termination minimizes the transfer impedance from backshell to inner cable conductors (pins). This paper presents a systematic study of the measured transfer impedance for a cable assembly with two layers of shielding topology from 1 kHz to 100 MHz using a quadraxial test fixture. The effect of terminating the inner most shield at different points in the backshell can be seen in the measurements. The results show, at frequencies where resistive coupling is dominant, that different termination points result in different transfer impedances. These differences are indicative of the differences in contact resistance for the backshell components. For only a single inner level of shielding, mutual inductance coupling is observed beyond 4 MHz. For two levels of shielding, the effect of mutual inductance coupling up to 100 MHz is insignificant. This data comparison shows that adding an additional shielding layer reduces the cable assembly transfer impedance by a factor of 10 beyond 4 MHz.

SHIELDING EFFECTIVENESS OF TYPICAL CABLES FROM 1 MHz TO 1000 MHz

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Cable shields usually have two specifications to meet one for EMP, and one for EMC. From 0 to 100 MHz the transfer impedance can be determined by using a simple voltage equation (ref. 1). This is an adequate technique for determining the shielding quality of a cable for EMP shielding analysis. Beyond 100 MHz the cable length is not electrically small and it becomes difficult to reduce measured data. Consequently, some form of shielding effectiveness is often used to specify the properties of cables. This suffices for determining the shielding quality for EMC analysis. Measured data for the shielding effectiveness (the ratio of center conductor to shield current) of several shielded twisted pairs and cable assemblies, from 1 MHz to 1000 MHz using a quadraxial test fixture, will be presented. The results show the shielding effectiveness reaches a minimum value which is directly proportional to the shield mutual inductance and becomes maximum at the cable electrical length resonances. The effect of a single aperture was also studied and measurements show the shielding effectiveness of this type of coupling is particularly poor at the UHF frequencies.

1. M. A. Dinallo, L. O. Hoeft, J. S. Hofstra, "Exploratory Cable Shielding Studies," BDM/A-81-568-TR, November 3, 1981.

STANDARD EMP TEST TECHNIQUES FOR
CABLES, CONNECTORS AND CONTAINERS

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This report presents the results of investigations into establishing standards for measurement of the electromagnetic pulse (EMP) shielding properties of shielded cables, their associated connectors and containers.

In the following material, two proposed standards are presented: Measurement of EMP cable and connector coupling parameters, and measurement of container shield quality. The proposed standards are followed by a discussion of some experimental data obtained by testing in accordance with the standards.

Ideally, a standard should describe tests in the quantitative measurement of meaningful parameters. That is, the test outcome should result in parameters which are useful to the design process, or verification purposes. The tests in the proposed cable and connector standard meet this requirement. The parameters to be measured are the transfer impedance per unit length between shield current and internal conductors, the coupling coefficient between shield charge and internal conductors, and the transfer impedance between a connector shell and internal conductors.

The proposed container standard, however, falls short: The primary reason for this is that the definition and measurement of meaningful container EMP parameters is considerably more difficult than for cables and connectors. While it seems possible to define meaningful parameters, considerably more experimental effort will be required before a practical standard can be written (one that describes practical tests to measure the meaningful parameters). Accordingly, the proposed container standard represents a compromise. The proposed tests can be performed in a reasonably expeditious way, and the resulting measurements (although not absolute worst case) can be applied to obtain practical estimates of induced voltages in circuitry enclosed by the containers.

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SURVEY OF EMP ASSESSMENT UNCERTAINTIES

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There are many uncertainties inherent in state-of-the-art EMP assessments. The uncertainties are associated with most elements of the assessment process and range from uncertainties in EMP environments to uncertainties in component susceptabilities. If the EMP assessment is performed in support of a system hardening program, the uncertainties translate to either risk in EMP hardness or additional hardening to accommodate the uncertainties.

This paper reports on a survey of the uncertainties which are included in the high altitude burst EMP assessment process for large, complex systems. The uncertainties are divided into categories to separate EMP induced stress uncertainties from threshold uncertainties. They are further divided into sub-categories separating actual system-to-system variances (eg.aircraft-to-aircraft differences in EMP coupling) from those uncertainties which are a reflection of the inability to precisely predict a given parameter (eg. the damage threshold of a piece-part).

Finally, a method is suggested for combining the uncertainties in such a manner as to estimate the fraction of a force of systems which will survive an EMP scenario with a given level of confidence. The procedure can be used to identify the hardening required to achieve a given success criterion.

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ASSESSMENT AND PROPAGATION OF UNCERTAINTIES IN SYSTEM EMP RISK ASSESSMENT

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The assessment of the risk of systems to an EMP threat involves uncertainties. There are the potential inherent random variations in the failure characteristics of components and systems as well as random uncertainties in the response of components caused by the EMP related stresses. Thus an analysis of the risk of a system to an EMP threat must allow for these random uncertainties. There are also uncertainties in the analysis and assessment of risk or vulnerability. For example, in most situations there is a lack of knowledge about the magnitude and location, relative to the system location, of the EMP source. There is also uncertainty in the transfer of the EMP induced stresses from the environment to the entry of the component/system. Finally, there is likely to be some uncertainty in knowing the parameter values associated with the random component failures. These uncertainties must also be considered in a risk assessment.

Much of the present EMP risk assessment does not distinguish between inherent random variation and model (analysis) uncertainties. Section 1 of this paper outlines how these uncertainties can be handled so that the resulting risk measure properly distinguishes between random and model uncertainties. Recognizing that much of the modeling information used in a risk assessment will be derived from experts, Section 2 includes a discussion of the problems related to assessing probabilistic opinions from experts. Development of expressions, which consider both random and model uncertainties, for the probability of failure of individual components is the topic of Section 3. Specifically, if the model uncertainties can be expressed in terms of lack of knowledge about the location parameters of the distributions of strength (threshold) and responses, bounds are developed for the probability of success, i.e., for the probability that safety margin exceeds zero. The last section of the paper discusses methods for developing bounds for the probability of failure of a system, i.e., a network of components.

*This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract #W-7405-ENG-48 and sponsored by the Defense Nuclear Agency subtask RR99QAXEC301, work unit 83; S/V Confidence Evaluation.

Abstract

A FAST PROCEDURE FOR THE EXACT COMPUTATION OF EMP AND OTHER ENVIRONMENTAL EFFECTS ON COMPLEX PROBABILISTIC SYSTEMS

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A new set-theoretic method for the exact and efficient computation of the reliability of complex systems has been developed.

The method is particularly suited for computing the effects of internal failures and uncertain environments upon large systems consisting of up to 1000 highly interacting parts.

The core of the method is a fast algorithm for disjointing a collection of sets and it is based on a "divide and conquer" approach where a multidimensional problem is progressively decomposed into subproblems along its dimensions. The method also uses a particular pointer system which eliminates the need to store the subproblems, but only requires to store pointers to those problems.

Examples of the algorithm and the divide and conquer strategy are provided, and comparisons with other significant methods are made. Statistical and worst case complexity studies show that the time and space complexity of other typical methods is $O(me^n)$, but that our method is $O(m^2n^2)$. Problems which would require 28 days of Cray 100 computer time with present methods can now be solved in about one second. Large-scale systems which can only be approximated with other methods can now be evaluated exactly.

RELIABILITY-CONFIDENCE FAILURE ANALYSIS OF SYSTEMS*

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Reliability-confidence failure analysis is important for large systems to assess the effects of disturbances such as EMP. Such analysis can be applied both to non-failure probabilities of network paths and to the probability of system failure over all disjoint paths of its network representation. For instance, the log-probability of non-failure over a network path is the sum of the log-probabilities of non-failure of the path components. The question then arises: given R-reliability intervals* for these component log-probabilities, and confidences in those intervals, what is a reasonable R-reliable interval for the path log-probability of non-failure and what is the confidence in it?

The same question is relevant to a study of the probability of system failure F as a sum of the probabilities of failure f_i over all its disjoint paths. Confidence statements about the R-reliable intervals of the f_i imply confidence statements abut various defined R-reliable intervals for F.

These matters will be discussed for Gaussian populations with known means and unknown but sampled variances. An advanced technique will be presented for computing the confidence in an R-reliable interval for a sum of independent Gaussian random variables given their sampled variances (J. V. Locasso, "The Confidence in Combinations of Imperfectly Known Variances", Prob. and Stat. Notes, Note 9, Air Force Weapons Laboratory, Kirtland AFB, 8 July 1977).

*i.e., an interval in which the log-probability is expected to lie 100R% or more "of the time" in an ensemble sense.

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A CANONICAL STUDY OF EMP VULNERABILITY

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A statement of the vulnerability of a system to EMP is dependent on the relationship between the system susceptibility threshold and the stress applied to the system. This paper approaches this problem from a probabilistic point of view by choosing a number of convenient canonical forms for stress and susceptibility threshold probability distribution functions and determining the resulting probability of vulnerability (i.e., the probability that the stress exceeds the susceptibility threshold). Possible relationships between these canonical forms and expected real-world distributions are discussed.

CONCEPTS FOR FLEET ASSESSMENT OF EMP HARDNESS

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Beyond the need for EMP assessment of individual systems lie the requirements for the assessment of entire fleets. Test planning and design for such an assessment must take into account the statistical nature of the testing process. This paper reports on test design concepts developed from a consideration of the requirements of such an assessment, and discusses the statistics of the related testing process.

ABSTRACT

Formal Technical Inferences About System Level EMP Hardness--Controversy and Confusion

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Past aircraft EMP test and evaluation programs have ended with no hardness assessment or with assessments embroiled in controversy. High level technical managers have claimed, on one hand, that EMP technology has matured and does not need high level expertise and, on the other hand, that a formal technical assessment of aircraft hardness is not yet possible. This paper sets aside both claims and examines hardness assessment issues inherent to large complex systems.

A heuristic discussion deals with aircraft EMP hardening, the use of analysis and test, the correlation between analysis and test results, and allowable statistical inferences. Particular emphasis is placed on the observed lack of correlation between EMP response and threshold predictions the corresponding test results, and the effect of that on hardening decisions and hardness assessment. The resolution of this problem is a hardening philosophy consistent with analytical capabilities and experimental resources; in short, there are some rather obvious dos and don'ts.

The trade-offs between requirements, degree of hardening, and formal evaluation methods are evaluated. The goal is to bridge the gap between the management and technical communities in a manner consistent with EMP hardening requirements and available test and evaluation resources.

PROTOCOL FOR EMP SURVIVABILITY STATEMENTS FOR C^3 FACILITIES

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The concept of a protocol for EMP survivability of systems is presented and the structure of the protocol framework defined. The protocol identifies the finite sets of decisions and their relative connectivity. The protocol structure is based on the key elements of an assessment: stresses (response drives), strengths (transient tolerance levels), comparison processes (hardness margins) and the accompanying uncertainties (experimental and analytical errors).

The protocol presented assures that certain desirable information is available to decision makers involved in assessments. These properties include: equivalence of measures of effectiveness, validity, and consistency.

EXAMINATION OF PROTOCOL STRUCTURE THROUGH EXISTING EMP ASSESSMENT DATA

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The protocol structure identified and defined in a companion paper is examined by employing existing EMP data. Certain characteristics desired in a protocol are examined in detail. The use of existing data complicates the examination since its accumulation did not occur under the protocol.

This examination is important in the process of verifying the utility of the protocol. Deviations from protocol procedures are noted. Evaluation of this variability will be performed.

SCALE MODEL AND FULL SCALE MISSLE
LIGHTNING TESTING

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Abstract

An extensive lightning test program has recently been completed on a major missile program. The testing was performed in two segments. The first segment consisted of testing a one-tenth scale model of a missile to determine probable lightning attach points. The second segment consisted of injecting simulated lightning strikes on a full scale portion of the missile. During testing, several missile response parameters were measured. The distribution of lightning current over the external surface was measured along with coupled voltages to externally mounted antennas. Measurements internal to the vehicle consisted of lightning induced cable shield currents and magnetic field distribution.

Two test waveforms were utilized for the second segment testing. The first was a damped oscillatory waveform with a fast rise time (approximately 300 nanoseconds) to simulate the high rate of change of current in the initial phase of a lightning return stroke. The second was a slower rise time (approximately 3 microseconds) unipolar waveform to simulate the high current long duration portion of a lightning return stroke first peak phase.

Instrumentation consisted of various derivitive sensors for measuring skin current, magnetic fields, cable currents and voltages. A fiber optics data transmission system provided instrumentation isolation from the hostile electromagnetic environment during test. Data waveforms were recorded and processed using transient digitizers and computer processing and storage. Several methods of analysis for the computerized data were evaluated, and are discussed.

This lightning test program is believed to be one of the most unique and extensive ever performed on any vehicle.

"AEHP For Advanced Aircraft"
AFWAL (FIEA/FIESL)

The Atmospheric Electricity Hazards Protection (AEHP) program of the Flight Dynamics Laboratory (AFWAL/FI) is being conducted through the Atmospheric Electricity Hazards Group (FIESL) for base-line investigations and the Advanced Development Branch (FIEA) to develop and demonstrate AEHP for advanced A/C electrical and electronic subsystems/equipments. Lightning characterization has been conducted using a NOAA C-130 during the 1979-81 "thunderstorm seasons." Airborne records have been made of 3-40 km distant lightning, as well as several direct strokes. Ground based records are also available for many events. These experiences indicate that portions of the return stroke current waveform associated with a cloud-ground lightning may have sub-micro-second rise-time high current peak pulses. It is planned to establish a simulation capability for 100 KA 200 nsec rise-time pulses through a fighter A/C. Initial efforts have demonstrated a 1.5 KA 200 nsec rise-time pulse through an F-16 A/C.

Currents/voltages induced in A/C information and power circuits during the A/C lightning/P-static interactions may cause upset/damage to advanced sub-systems/equipment. Fiber-optics data links are being investigated as a counter to this threat. The AEHP Advanced Development Program (ADP) will continue development of this and other protection concepts. After specifying design criteria and establishing the design of AEHP for mission critical/flight-safety elements of A/C the hardness achieved will be demonstrated using appropriate atmospheric electricity threat simulation.

AIRCRAFT LIGHTNING STRIKE CHARACTERISTICS

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ABSTRACT

Because of the weight, cost and performance penalties which can result from overdesigned lightning protection, it is important that the atmospheric electricity threat be accurately characterized so that protection for aircraft can be optimized without compromising flight safety. Lightning design and test specifications for aircraft are based upon lightning discharge parameters measured on the ground during cloud-to-ground discharges. For conservatism, the most severe cloud-to-ground parameters are used in the specifications. Recent measurements imply that the specifications should include very fast risetime values, making then even more severe. An examination of aircraft operational statistics indicates that the involvement of aircraft in low altitude cloud-to-ground flashes may be very rare. Most strikes are reported to occur while aircraft are flying at the freezing level in or around precipitating clouds. Reports of strikes to aircraft flying below a few thousand feet are very rare in the U.S.

The probable characteristics of lightning discharges experienced at the aircraft are discussed and are argued to be quite different from those which would be measured at the ground for natural cloud-to-ground lightning. The projected characterization draws upon intracloud discharge parameters, theroretic1 considerations, the parameters of triggered lightning discharges to wire-trailing rockets, limited in-flight measurements of strikes to aircraft, and, finally, examinations of lightning damage markings on aircraft.

The importance of the altitude issue to the discussion of lightning discharge characteristics is threefold. First, the presence of the aircraft in the cloud in close proximity to charge centers enhances the probability of triggered lightning. Triggered lightning can be argued to have discharge parameters different from those of natural cloud-to-ground strokes. Second, at cloud altitudes, the probability of a strike to the aircraft being a cloud-to-ground flash is reduced since intracloud discharges are more numerous. Intracloud discharges are known to be less energetic than cloud-to-ground discharges. Third, at flight altitudes, the parameters of a cloud-to-ground flash are expected to be much reduced from their values near the ground. High peak current discrete pulses involve the transfer of charge stored on the ionized channel which generally extends from around the freezing level in the cloud to the ground. If the aircraft is at the upper end of the channel, then the charge on the channel will be almost entirely below the aircraft, resulting in reduced return stroke parameters.

It is predicted that the aircraft will always experience a continuing current discharge due to the leader currents feeding through the aircraft. In some cases, low to moderate level discrete pulses (average 2 to 5 kA, worst case 50 to 100 kA) with rise times from a few to several microseconds will be experienced. These predictions compare favorably with the available measurements of direct lightning strikes by instrumented research aircraft and with damage reports to operational aircraft.

SHOCK EXCITATION LIGHTNING TESTS OF FULL SCALE AIRCRAFT

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The pulsed current and shock-excitation lightning simulation techniques were used to analytically and experimentally evaluate the response of high impedance differential wire pairs in a controlled geometry laboratory test and in a full-scale fighter aircraft. The program consisted of three major tasks.

1) Conduct both tests under similar conditions on a long aluminum cylinder in the McDonnell Aircraft Company's high-voltage laboratory.

2) Analyze each test condition theoretically and correlate the results with the experimental data.

3) Move the same test equipment to Wright-Patterson Air Force Base (WPAFB), and repeat the tests on the YF-16 fighter aircraft.

The shock-excitation test configuration differs from the pulsed current test configuration by insulating the aircraft from ground and by incorporating an output spark gap between the test article and the ground return system. The spart gap isolates the test article from ground potential so that the structure is first raised to high voltage and then quickly discharged when the spark gap breaks down.

The cylinder tests and analyses demonstrated that capacitive (C dV/dt) coupling is the principal coupling mechanisms for the high impedance interior circuits. Transmission line effects were found to be very important for both test techniques with the induced voltages being approximately an order of magnitude higher for the shock-excitation case. The fast discharge of the shock-excitation technique quickly changes the output impedance of the cylinder/return conductor transmission line from a high impedance to a near short circuit. This transition strongly excites the cylinder transmission line resonances. As the generator charge voltage and output gap length were changed, the induced voltage excited on the interior wires varied as the time rate of change of the cylinder voltage during gap breakdown ($\approx$ dV/dt).

The analysis of the cylinder test configuration demonstrated that both the pulsed current and shock-excitation test techniques can be modeled as two coupled transmission line circuits with either distributed or lumped components. The analytically predicted transients agreed well with the experimental data.

Limited aircraft tests on the flight control circuits of the YF-16 produced waveforms and scaling relations similar to those of the cylinder. The fast discharge of the shock-excitation technique produced near threat level values of 10^{11} A/s and 10^{12} V/s. Differential induced voltages on the flight control circuits were only a few volts.

FULL-LEVEL LIGHTNING AIRCRAFT SYSTEM HARDENING (FLLASH)
FOR ADVANCED COMPOSITE PLATFORMS

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The (1965) design of the F-14 fighter initiated major deployment of advanced composite materials for a total aircraft section. The F-18 (1975) design saw 12.1% by weight and 38% by surface area construction from composites combined with digital fly-by-wire control. The Lear FAN 2100 jet is 100% composite. Future aircraft, missiles and helicopters will contain approximately at least 80% composites as evidenced by the Army's All-Composite Airframe Program which is developing an almost all-composite graphite/epoxy and an almost all-composite kevlar helicopter. The significant reduction in electromagnetic protection in fair to non-conducting composite structural materials combined with flight safety dependence on computer control has sparked significant interest in establishing the electromagnetic hardness of composite platforms in lightning and the nuclear EMP. The hardness of frozen composite aircraft designs will be measured and future designs will consider these concerns in the very early design phase. The Navy's Electromagnetic Design and Synthesis (EMDAS) program is implementing early design hardening trade-offs in the HMX, VSTOL and VTXTS procurement program while the Full-Level Lightning Aircraft System Hardening Program (FLLASH) is measuring lightning hardness on the F-14, F-18 aircraft, AIM-9L missile, and a to-be-determined helicopter. These results will then refine EMDAS as well as evaluate the hardness variation of the full-scale aircraft with sections of different non-metallic materials. By considering the protection needs imposed by disciplines other than EMP or lightning (i.e., heat, life cycle, structural integrity, and laser protection), designs satisfying more than one area are being evolved that truly optimize protection/weight penalties.

During FY-82 and FY-83, the Navy F-14 and F-18 aircraft will undergo full level EMP, lightning, SCIT and CW current injection tests. To date both the THREDE[1] and the triangular surface patch modeling[2] have been applied to the F-14 and are currently being applied to the F-18. This paper discusses available results from these efforts with particular emphasis on the significance of:

- Threat rise time variation
- Material type and distribution variation
- Material joint bonding variation
- Comparison with measured results

[1] R.Holland, "Threde: A Free Field EMP Coupling and Scattering Code", IEEE Trans. Nuclear Science, Vol. NS-24, pp 2416-1421, December 1977

[2] S.M. Rao, "Electromagnetic Scattering and Radiation of Arbitrarily-Shaped Surfaces by Triangular Patch Modeling", PH.D. Dissertation, The Unviversity of Mississippi, August 1980

EXPERIMENTAL CHARACTERIZATION OF WIRE INDUCED CURRENTS FROM BULK CURRENT MEASUREMENTS*

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Characterization of wire responses are usually required in order to evaluate the survivability of a system. This information can also be used for preliminary assessment purposes as well as a basis for test point identification and selection to focus system level test planning efforts. These wire responses are typically inferred from bulk currents which are calculated from complicated computer code models which require extensive data consisting of source terms, load terminations and wire routings. There are many expressions that can be used to infer a wire response from bulk calculations. However, these expressions or ratios have been calculated from connectors whose sampled wire measurements have been less than 100%.

This paper presents the results obtained during the recent F-14A System Test of bulk current measurements and wire current measurements on all wires in several cables. The bulk measurements and respective wire distributions are shown. From these data bulk-to-wire scaling ratios are developed, and factors affecting bulk-to-wire ratios are discussed. Comparisons between these ratios and those developed from previous test programs are also presented.

* This work was sponsored by the Defense Nuclear Agency Contract DNA001-81-C-0093.

THEORETICAL AND EXPERIMENTAL RESPONSE ANALYSIS OF PERSHING II MISSILE SYSTEM CABLES TO AN EMP ENVIRONMENT

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Many of the Army systems that are presently being appraised for high-altitude electromagnetic pulse (EMP) vulnerability and hardening are configured with signal and power cables that extend between system equipment and radiate out from the system when it is tactically configured. These long cables tend to be maximum energy couplers and prime points of entry for the EMP signals. System analysis techniques to appraise vulnerability must rely on circuit analysis codes to predict system upset and damage. Transmission line network (TLN) representation of system energy drivers is an extremely efficient, accurate, and compatible method of introducing EMP-coupled energy to these circuit codes.

This paper discusses the free-field TLN analysis of a set of shielded, multiconductor cables that interconnect the three missile erector launchers, the platoon control center, and the power generators of the Pershing II missile system. The cable TLNs have been developed by using the results of the transmission line code FREFLD[1] and the scale model facility at the Facility for Research in Electromagnetic Effects (FREME).[2] Moreover, the TLN code was modified to include the modelling of the inner conductor of the shielded cables whereby the internal voltages can be calculated. The EMP responses of the cables were obtained with the scale model on a turntable so that a sufficient combination of orientations and exposures was performed to validate the cable TLNs.

The development of the TLN representation for multiple, interconnected system cables represents an important improvement in dealing with the vulnerability analysis of any system. Comparisons of the calculated and experimental results will be presented.

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[1] R. Gray, The EMP Response of a System of Uncoupled, Interconnected Cables, Harry Diamond Laboratories, HDL-TR-1903, Oct. 79.

[2] A. Cuneo, Jr., J. Loftus, Measurement of Scaled-Down High-Altitude Electromagnetic Pulse (HEMP) Waveforms, Harry Diamond Laboratories HDL-TM-81-6, Mar. 81.

CURRENT DISTRIBUTION IN SHIELDED MULTICONDUCTOR CABLES

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Mititary systems commonly use multiconductor cables. Determining the response of these systems to EMP often requires estimates of signals on individual conductors. This presentation addresses a multiconductor cable with a flexible metal braid external shield. Internal conductors consist of shielded twisted pair (STP) conductors whose shields are coterminated to the overbraid at each end.

The model consists of a transmission line with a uniformly distributed voltage source due to external current excitation of the overbraid transfer impedance. The internal conductors are modeled(1) as a stranded conductor. This model is appropriate when the bundle cross section consists of a large number of uniformly distributed conductors. In addition, inductance proportional to the length of each STP shield termination is added at each end of the individual conductors.

Experimental data is based on a one meter section of overbraid with 19 STPs arrayed in three concentric layers. The STP shields were coterminated with the overbraid at each end. The terminal common mode voltage response of STP internal conductors was obtained in the 10^3-10^8 Hz range using a quadraxial test fixture.

Comparison of model and test results is favorable. Results show three phenomena. Below 10^4 Hz, the response is uniform. Between 10^4-10^6, results show a skin effect type response with maximum response on the outermost conductors. Above 10^6 Hz, the response is dominated by shield termination inductance.

(1) Kaden, H., Wirbelströme und Schirmung in der Nachrichtentechnik, Springer-Verlag, 1959.

THE COUPLING OF ELECTROMAGNETIC FIELDS TO MULTICONDUCTOR CABLES*

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A problem of continued interest to the radiation effects community is the coupling of electromagnetic fields to multiconductor cables. The material and geometrical complexity associated with realistic multiconductor cable configurations has heretofore precluded the possibility of performing a detailed analysis of the distribution of expected currents and voltages.

In this paper, we will report the results of a series of calculations performed on model multiconductor cables using the COUPLE[1] code. This code has been developed to calculate the capacitance and inductance matrix and the "effective" heights of arbitrary multiconductor cable configurations. The results of these calculations, in combination with the incident electromagnetic fields, provide the distribution of current (E-field) and voltage (B-field) sources which can then be used to drive a multiconductor transmission line code to obtain the distribution of currents and voltages. Under certain simplifying assumptions (short circuit termination impedances, spatially uniform electric and magnetic fields, and a single propagation mode), it can be shown that the distribution of currents scales with the coupling capacitances C_i, i=1,N, where:

$$C_i = \sum_{j=1}^{N} C_{ij} h_j \quad ;$$

C_{ij} are the elements of the capacitance matrix; h_j, the "effective" height of the j^{th} wire; and N, the number of wires in the multiconductor cable. An analysis of the coupling capacitance as obtained from the COUPLE code will then provide sufficient information to quantify the distribution of currents.

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(1) J. E. Tigner, et al., IEEE Trans. Nuc. Sci., NS-27, No. 6 (1980).

*Work supported by the DEFENSE NUCLEAR AGENCY under Contract Number DNA001-81-C-0005.

A PARAMETRIC STUDY OF THE RELATIONSHIP OF INDIVIDUAL WIRE SHORT-CIRCUIT CURRENTS TO CABLE BUNDLE CURRENT IN MULTICONDUCTOR CABLES

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Of particular interest in large system EMP analysis is the applicability of using bulk current measurements to bound the values of wire currents within the wire bundles. The issues addressed in this paper are: (1) the effects of termination impedance at the far end of a wire on the short-circuit current being measured; and (2) the relationship of variability (ie. amplitude and frequency content) of the bulk current to the variability in short-circuit current.

A multiconductor transmission line code based on the works of Sidney Frankel was run to study the desired parameters under various load and cable configurations. The results of this investigation are compiled to provide a first estimate of the applicability of using bulk current measurements for bounding the short-circuit currents used in EMP vulnerability assessments.

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R. E. Matick, Transmission Lines for Digital and Communication Networks, McGraw-Hill Book Company, 1969.

CABLE CURRENT BOUNDING IN AIRCRAFT EMP TESTS

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A preliminary empirical investigation into the relationship between peak time-domain pin (wire) currents and the corresponding peak bulk currents indicates that a bounding relationship may exist; that is, the peak pin current is not more than a (to be specified) multiple of the corresponding bulk cable current. Furthermore, the available data suggest that this bound may be independent of aircraft excitation level.

The limited data base available precludes meaningful statistical confidence to be assigned at this time. In addition, no data was available on small aircraft, so that extrapolation from one aircraft type to another is not possible. Nevertheless, the results strongly suggest that additional tests (designed with the bounding objective in mind) should be done, so that a quantitative confidence can be associated with the resulting bound.

The concept of cable current bounds falls naturally into the domain of non-parametric statistics. A random variable is defined as the maximum peak wire current in a cable. This variable, together with the corresponding peak bulk cable current, are plotted as scatter plots. The bound appears as a straight line in these plots, and non-parametric statistics are applied to the results.

The establishment of a bounding relationship has many implications. For example, one only has to measure bulk cable currents, thus, either much more data can be obtained for the same resources, or the amount of data taken can be reduced. In either case, quantitative confidence in hardness will result.

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BOUNDS ON CURRENTS AT TERMINATIONS OF A MULTICONDUCTOR TRANSMISSION LINE EXCITED BY AN EXTERNAL FIELD*

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An expression for an upper bound for currents at terminations of a multiconductor transmission line excited by an external field is presented. The currents at terminations depend on several parameters; these include incident field, physical parameters of the transmission line and the surrounding medium, and the load impedances. To obtain a bound for termination currents, norms of matrices and vectors are used. The bound for termination currents is expressed in terms of bounds for load impedances, the characteristic admittance matrix of the transmission line, and the distributed sources.

*This work supported by the Air Force Weapons Laboratory under contract F29601-78-C-0082.

Solution of Transient Multiconductor Transmission Line Problems by the Use of Diakoptics

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ABSTRACT

The solution of problems involving transients on multiconductor transmission line networks is complicated because of the coupling which exists between the lines at the junctions. The method of Diakoptics, which was developed by Kron in the 50's [1] allows a system to be split into parts such that the coupling is not present and these parts can be solved individually. These uncoupled solutions, along with the topology of the interconnections, are then used to generate the solutions to the original problem. An example showing the application of the procedure to a sample system is given.

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(1) G. Kron, Diakoptics, The Piecewise Solution of Large-Scale Systems, MacDonald, London, 1963

DIAKOPTIC TECHNIQUES APPLIED TO BRANCHED CABLE MODELING

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The transient effects of lightning, EMP, and SGEMP on branched cables are commonly analyzed using models composed of parallel combinations of distributed and lumped networks. This paper presents an efficient solution technique for calculating the equivalent impedance and node voltages of such systems. The technique, currently being extended for application to non-linear SGEMP analysis, is based on the theory of diakoptics and Householder's method of modifying matrices.

In essence, the concept of diakoptics is to solve a large network by first dividing it into subnetworks, then solving each subnetwork separately and using Householder's method of modified matrices to arrive at the correct solution of the entire connected network. These steps are illustrated through an example problem consisting of a transmission line that branches. First, this system must be divided into lumped and distributed networks. The termination impedances and the impedance discontinuity introduced by the cable branching are each represented as a lumped network. Each of the transmission line sections are modeled as distributed networks. The second step is to compute the open circuit impedance matrices and voltage vectors for the seven separate networks. This is performed analytically for distributed networks and by classical network theory for lumped networks. The last step in the solution process uses a simple algebraic equation, known as Householder's method, modifying these subnetwork parameters to produce the equivalent impedance matrix and voltage vector of the connected network. The same example problem was solved using common transmission line ladder network models.

Comparing the example problem results obtained from each of the solution methods illustrates that the diakoptic technique was accurate and identified the following advantages:

1. After determining the equivalent impedance matrix and voltage vector of a connected system, other networks can be added to the system without starting over.
2. Identification of subnetworks is simple, therefore, the process of setting up the problem is easy.
3. Since small matrices and simple algebraic manipulations are used significant amounts of computer time and storage are saved in using the diakoptic technique. This is especially true when solving large scale problems.
4. Unlike the ladder network model, the diakoptic technique does not decrease in accuracy with increasing frequency.

SIMPLIFIED EMP SYSTEMS ANALYSIS USING A PROBABILISTIC CIRCUIT ANALYSIS CODE

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A revised version of the Air Force Weapons Laboratory - HANAP EMP Circuit Analysis Code was developed.[1] The revised version included a probabilistic assessment capability based on a Kaman Science Corporation developed methodology.[2] A method of accounting for estimates of empedance mismatch was also developed. The revised code includes the following principal features in addition to the basic capability of calculation of the component failure level parameters and two-port network transfer function:

- Component failure-power levels with probabilistic models for range of data quality
- Circuit transfer function with uncertainty for model validity
- Source amplitude probabilistic distributions
- Source/circuit impedance mismatch effects
- Hardness margin distribution
- Pin level probability of survival calculation
- File search for source and component data to insure consistency and ease of data updating

The presentation will include a summary of potential application to system analysis including:

- Circuit screening
- Sensitivity studies
- Pin level probabilistic survival predictions

The code was used in failure screening analysis for over 10,000 circuit predictions for the B-52 system.

1. The BDM Corporation, BDM/TAC-80-630-TR, HANAP5 User's Manual, October 30, 1980.

2. B-52 Aircraft HPD/VPD System Level Test (Phase II) Post Test Analysis SDRL-A-026 and A-027 (SECRET); Wolfgang Berenter, Kaman Sciences Corporation, March 20, 1980.

ESTABLISHING MINIMUM BURNOUT THRESHOLDS

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Recent EMP assessments have used probabilistic methods to assess the EMP susceptibility of systems and to support determination of hardening requirements.[1] In the probabilistic approach, analyses and/or tests are used to estimate probability density functions for the EMP induced stresses and circuit burnout thresholds. The appropriate density functions are then used to estimate pin survival probabilities which are in turn used to determine hardening requirements.

If continuous probability density functions are used, the distribution tails (far from the means) often control the survival probabilities and hardening requirements, even when there are no data or physical models to support the shape of the extremes of the distributions. In such cases, the probabilistic approach can lead to an inappropriate set of hardening requirements.

In this paper, a procedure is presented for establishing minimum burnout thresholds. The minimum burnout thresholds can be used to truncate the threshold probability density functions thereby reducing or eliminating the sensitivity to the extremes of the distributions. It is shown that, for many circuit topologies, the minimum burnout threshold is a function of only breakdown voltage and the circuit topology. Thus a detailed parts damage model and associated parameter values are not required. Several examples are shown to illustrate how the minimum burnout thresholds are established.

This approach, in the context of a total system hardening problem, potentially impacts the assessment approach, the hardening requirements, the hardening approach, and the hardness assurance, maintenance, and surveillance procedures.

1. D. Guice and J. Lubell, "B-52 EMP Hardening Program," DNA EMP Simulation and System Hardening Symposium, October 1980.

* This work partially supported by the Defense Nuclear Agency under Contract No. DNA001-80-C-0354.

ABSTRACT (NEM)

"USING LIMITED SAMPLE EMP DAMAGE THRESHOLD TEST DATA"*

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Conclusions and inferences which may be made based on single-sample "black box" EMP damage threshold data are presented. The conclusions result from using the test data in an aggregate sense as a measure of analytical prediction capability. The results are largely based on statistical techniques as described by Ashley.[1]

Tests were performed at the AFWL direct-drive laboratory to determine damage thresholds on approximately 200 circuits from a sample of 22 B-52 LRU's. Test results will be presented along with a comparison to the circuit analysis technique used to provide pre-test failure predictions. Although on an LRU by LRU basis the confidence/reliability figures for the damage threshold are low, when the test data are aggregated and viewed as a measure of the analysis validity a sufficient sample size is available to state high confidence conclusions. For example the results indicate that there is 90% confidence that better than 99% of the analyses will be within a known small error margin. The analysis attempts to maximize the payoff from the test by using laboratory failures as well as the more populous no-fail data. Statements which can be made with low confidence concerning individual circuit thresholds will also be presented.

[1]Ashley, C., "Confidence and Reliability in an Infinite Population," System Design and Assessment Notes, Note 3.

*Work performed as part of Air Force contract F33657-80-C-0060 under subcontract B-B01285-9166 to the Boeing Military Airplane Company.

DETERMINATION OF FAILURE DISTRIBUTION PARAMETERS FOR EMP CIRCUIT ANALYSIS

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The analysis techniques for system response in an EMP environment have been continuously refined. Circuit response models for high injected current levels are more accurate. A great deal of test data from direct drive of components and subsystems and EMP simulator drive of systems have been collected. With this additional data it has become worthwhile to attempt to make probabilistic calculations for hardness margins or probabilities of survival. To perform such calculations one would like distributional data both for the source drive and for the component failure.

As a part of the B-52 EMP Assessment Program a study was made of the component failure distributions. This paper presents results of that study.

Failure analysis of semiconductor devices in the B-52 program used the lognormal distribution for both the drive and failure threshold distribution. Conservative estimates of the parameters of the lognormal distribution were used in the analysis. The mean of the failure threshold distribution was chosen by employing failure models and semiconductor test data. A conservative standard deviation was chosen, which was a function of the mean by examining the spead of test data semiconductor failure distributions. Since estimating parameters are not exact, the analysis also considered distributions on the mean and standard deviation. Folded normal distributions were used, where the estimate of the mean is the mean of the normal distribution and a standard deviation for the normal distribution was estimated which represented the spread of the mean. This methodology allowed probabilities of survival to be calculated by random sampling of the normal distribution. All parameter estimation in the analysis was performed to yield statistical inferences with 90 percent confidence.

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2. D. R. Alexander and E. W. Enlow, "Predicting Lower Bounds on Failure Power Distribution of Silicon NPN Transistors," IEEE TRANSACTIONS ON NUCLEAR SCIENCE, Vol. NS-28, December 1981.

EOS/ESD FAILURE THRESHOLD ANALYSIS ERRORS, THEIR SOURCE, SIZE, AND CONTROL

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Abstract

Circuit EOS/ESD failure thresholds define the minimum overstress level required to damage a semiconductor. The thresholds are calculated using conventional circuit analysis and semiconductor device damage models, which are synthesized from experimental data, and are based on the principles of semiconductor device physics. This paper examines the accuracy of calculated failure thresholds, identifies the source and magnitude of analysis errors, and suggests techniques for improving analysis accuracy.

How can we minimize the uncertainty in analytically determined failure thresholds? First, assuming that the population variation is not excessive, appropriate specifications could be placed on device parameters. For example, destructive testing could be done on a sample of devices to establish acceptability. Alternative appropriate non-destructive measurements could be used if these can be shown to accurately predict failure thresholds. We should also determine and use such non-destructive measurements to calculate failure thresholds, and to minimize estimation errors.

The main source of the uncertainty in calculated failure threshold is due to the inaccurate device failure models. A first order improvement in models may possible be achieved by understanding electrical second breakdown. Does electrical second breakdown really occur in electronic systems subjected to a short time duration threat? If not, then the failure modeling problem may be much less complex.

Many other sources leading to variability and errors in calculated threshold can be controlled by using presently available techniques, while others will require further work.

Errors in device failure modeling, probably due to different failure mechanisms, controlthe accuracy of failure threshold analysis beacuse techniques and procedures are available to make errors in all other elements of failure threshold analysis small. An enhanced understanding of failure phenomenology based on principles of device physics is pivotal to improving the accuracy of calculated EOS failure thresholds.

A HIGHLY EFFICIENT CONDUCTED SUSCEPTIBILITY TEST PROCEDURE*

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The procedure for verifying that electronics boxes meet their EMP and SGEMP conducted susceptibility requirements has taken many forms. For a complex system, built by multiple associate contractors, this results in inefficiencies in interpreting the data and comparing the data to specifications. The purpose of this paper is to describe a concept of standard current injection test procedures. If adopted, these standard procedures would facilitate the use of common test equipment, coupling methods, and approaches to data interpretation.

The proposed standard emphasizes minimization and simplification of test configurations and test waveforms while still satisfying the verification requirements. For instance, the specific case analyzed has interface requirements described as a continuum of damped sinusoids for EMP and a set of trapezoids for SGEMP. In order to evaluate equipment, using previous test methods, a very large number of test waveforms, both sinusoids and trapezoids, would have to be generated. However, our method requires only three waveforms (typical), and the waveforms need only be trapezoids. Our method is straightforward and can be used with any set of system specifications. In our specific case, the EMP sinusoids and SGEMP trapezoids are merged in the frequency domain into an overall peak envelope. Then, a set of trapezoidal waveform transforms are "fitted" to the envelope, resulting in a minimum set of test waveforms. Drawbacks do exist, and the resulting impacts and trade-offs are discussed in detail for our specific case.

The proposed standard procedure also defines a minimum set of test configurations, including: common and differential mode passive testing, common and differential mode upset testing, and burnout testing. A complete set of guidelines are given which identify the configurations which are necessary and sufficient for any given case.

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WAVEFORM CONVERSION TECHNIQUES FOR EMP-INDUCED PIN SIGNALS

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ABSTRACT

Interface circuit EMP damage thresholds are commonly expressed in terms of damped sinusoidal waveforms. The EMP-induced interface waveforms measured in the course of system-level EMP tests are usually rather complicated, broad-band signals. This paper deals with techniques for converting EMP-induced waveforms into damage-equivalent damped sinusoids so that interface safety margins can be derived using the same waveform.

Four thermal response models are derived using Duhamel's linear, transient heat transfer theorem and general semiconductor device thermal damage parameters. These models are first applied using a damped sinusoid to obtain functions which describe the major features of the resulting thermal response. Next it is shown that the thermal response produced by typical EMP-induced waveforms can be adequately approximated by the same functions. Thus the thermal models provide damage equivalence relationships between EMP-induced waveforms and damped sinusoids.

Application of the method is illustrated using waveforms measured in the B-52 EMP Baseline Test. The techniques do not depend on detailed knowledge of specific devices since the parameters of the damage-equivalent damped sinusoids are not strongly dependent on the thermal model used. For example, the amplitudes of the damage-equivalent damped sinusoids produced by the four thermal models agree within a few dB.

The method produces a two-parameter family of damage-equivalent damped sinusoids. For most interface circuits the remaining free parameter can be selected in a variety of ways without significantly affecting the resulting safety margin calculations. Several possible methods of selecting the free parameter are presented and their implications in EMP assessment discussed.

In sum, the method is completely general, is based on fundamental device thermal damage characteristics, and is computationally easy to implement. The application of these techniques in system-level EMP assessment and testing is illustrated and described in detail.

MODELING BURIED CIRCUIT COUPLING WITH THREE WIRE TRANSMISSION LINE THEORY

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Techniques for predicting the damage threshold of electronic systems exposed to nuclear weapon electromagnetic pulse (NEMP) induced current and voltage waveforms rely on available schematic diagrams for a description of the circuitry. Unfortunately, these schematics do not include the parasitic elements that play a major role in determining the circuit response to the higher frequencies of the NEMP excitation. Neglect of these parasitics during an assessment will generaly result in underprediction of the circuit damage thresholds because the parasitics function to shunt energy away from the sensitive devices imbedded in the circuit. However, in some cases the parasitics may serve to couple energy a sensitive area of the circuit which, according to the schematic, is well isolated from the excitation port. This portion of the circuitry is called a "buried circuit." In the case of buried circuits an analysis based solely on the circuit schematic may result in overprediction of the damage threshold which is unacceptable. In this paper three wire transmission line theory (C. R. Paul, IEEE Transactions on Electromagnetic Compatibility, Volume EMC-20, No.1, February 1978) is used to model buried circuit coupling and the role termination impedance and conductor geometry play in determining the nature of the solution is explored. Then a "worst case" configuration is examined and the result is screened against the failure levels of a number of commonly used part types for several input threat levels. It is shown that for threat levels on the order of a few amps in a system of moderate complexity, buried circuit failures, if they occur at all, will occur only in a few isolated cases. Finally, a methodology for catching these isolated cases which utilizes system level test results and the results of an analysis performed on the basis of circuit schematics is proposed.

FAILURE ANALYSIS OF SEMICONDUCTOR DEVICES IN EOS/ESD TESTING

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Electrical overstress/electrostatic discharge (EOS/ESD) testing of electronic systems is frequently employed to confirm the accuracy of analysis predictions of circuit failure thresholds. This paper presents a procedure to probabilistically determine whether these test-induced failures were due to normal test procedures or some unidentified action. The analysis consists of a combination of physical examination and electrical and thermal analysis of the failed device to determine the probable level of failure and the mechanism and site of failure.

Presented here is a description of the analysis procedures and their application to a semiconductor part that failed during an aircraft subsystem EOS test. The major elements in the failure analysis consist of (1) inspection of the device through microscopic examination for physical anomalies, (2) hand and computer analysis of the device chip, and chip to header, and (3) probability statement of the failure results.

A COMPARISON OF THE COMPUTER RESOURCE REQUIREMENTS AND PERFORMANCE OF SEVERAL FINITE DIFFERENCE PROBLEM SPACE BOUNDARY CONDITIONS

BY

ROBERT FISHER

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ABSTRACT

This paper will compare the computer resource requirements and relative performance for several boundary conditions suitable for truncation of finite difference grids in EMP calculations. Comparisons will be made of the "soft lattice" condition used by Taflove and Brodwin [Ref 1], the far field radiation treatment by Merewether [Ref 2] and the "highly absorbing" condition recently proposed by Mur [Ref 3].

The soft lattice condition extrapolates back stored fields at points inside the boundary to the grid boundary. This technique also incorporates field averaging to minimize the effect of variations in the angle of incidence of the outgoing wave at the boundary. The radiation condition extrapolates fields inside the grid to fields at the boundary by assuming that only outward going waves are present: $E^S = f(t-R/c)/R$. The radial attenuation of the fields is an important improvement over the soft lattice condition in many problems, but this approach does not yield good results when the problem space boundary is very close to the extremities of the scatterer.

The highly absorbing boundary condition uses a second order approximation for the boundary fields derived from the scalar wave equation. This technique takes into account the propagation direction for the outgoing wave but does not treat the fall-off of the amplitude with distance.

The relative computer memory requirements and required execution time for each boundary condition will be compared. Also, the relative accuracy of the computations will be compared for sample problems in two-dimensions.

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MODELING THE X-RAY DEPOSITION REGION BY NUMERICAL INTEGRATION OF THE BOLTZMANN EQUATION

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Abstract

Most numerical solutions of the X-ray deposition problem have involved either cloud-in-cell macroparticle techniques or prescribed source techniques. Macroparticle approaches often require 10^4 - 10^5 particles to reduce the simulation noise to a reasonable level and therefore can be quite costly for a multi-dimensional problem. Prescribed source techniques are cheaper but do not achieve a self-consistent solution. More recently, attempts have been made to model the X-ray deposition region by a set of fluid equations. This approach offers large savings in computer time but requires assumptions on the form of the distribution function. An alternate approach is to integrate the distribution function directly. This approach has been discussed by Higgins, Longmire and O'Dell[1] and was used by Holland[2] to investigate the effects of secondary electron emission.

In this paper, the Boltzmann equation in the form

$$\frac{\partial f}{\partial t} + \overline{w} \cdot \overline{\nabla}_r f + \overline{\nabla}_w \cdot (\overline{a} f) = \text{Sources} - \text{Sinks}$$

will be numerically solved on a LSI 11/23 processor by weather differencing in two spacial dimensions. The algorithm is stable and allows arbitrary object boundary conditions to be installed in a natural manner. The response of a cylindrical cavity to X-ray induced electron emission at various air pressures and pre-ionization levels will be shown.

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NETWORK ANALOG SOLUTION OF MAXWELL'S EQUATIONS
IN CONDUCTIVE MEDIA

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In recent times network analogs have become an increasingly popular tool for solving the differential forms of Maxwell's equations in one and two special dimensions. For problems exhibiting azimuthal symmetry, a network analog has written that is relatively straight forward to implement on a circuit code.

Maxwell's Equations are first written as incident and total fields to include the current density from conduction $\bar{J} = \sigma\bar{E}$, and any source current terms, $\bar{J}$. The difference between these two sets of equations yields the scattered fields as a function of the incident fields. These equations are, in turn, rewritten in finite difference form. By redefining terms, the equations are cast into a network analog form. The electric and magnetic field variables are transformed into those of current and voltage, respectively. The analog has a resistance in the R and Z directions that is proportional to the conductivity of the particular medium. The incident electric field is transformed into a voltage source that is also proportional to the conductivity.

Conductive boundary conditions are met by making the connecting resistors very large so that the tangential electric field (current) goes to zero. At the free space boundary, the terminating resistance is given by the characteristic impedance of the transmission line.

An overview of the network analog approach will be presented. The appropriate network analog will be applied to several examples including a dipole antenna in free space, an antenna in a conductive medium and an antenna over a ground plane.

APPLICATION TO MODEL ORDER REDUCTION TECHNIQUES TO NON-LINEAR NETWORKS

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The techniques of model order reduction were originally derived for use on large scale linear resistive circuits. By combining these techniques with the Newton-Raphson iteration scheme, it is possible to achieve many of the advantages of model order reduction for nonlinear problems.

As in the linear case, we consider a lumped distributed network, break it into pieces, compute solutions on the pieces, and then combine the solutions. However, in the nonlinear case, the admittance function used is not a matrix so that Householder's method cannot be applied directly, but it can be used effectively with Newton-Raphson.

One of the drawbacks to Newton-Raphson is that it requires the inversion of a Jacobian matrix which changes with each iteration. For a large network problem, this matrix may be quite extensive, which frequently makes use of Newton-Raphson prohibitive.

One straightforward application of model order reduction is in this inversion, by removing nonlinear branches from the network, computing the solution on the linear portion and then reinstating the nonlinear branches one at a time, model order reduction formulas may be used to increase the speed of the Newton-Raphson. In addition, by first solving the linear portion of the problem and using its solution as the initial guess, it becomes possible to reduce the size of the problem given to Newton-Raphson by eliminating all but those nodes directly involved in the nonlinearities. This then mimics the linear model order reduction in its saving in space and its conceptual advantages.

A thorough exposition of the technique as well as an example of its application will be provided.

A FINITE DIFFERENCE APPROACH TO APERTURE MODELLING IN ELECTROMAGNETIC COUPLING CODES

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A powerful alternative to the traditional analytical and/or numerical (method of moments) formulation of electromagnetic aperture coupling problems is the finite differenced time domain technique of computer solution. The technique involves solving the initial value problem of a scatterer irradiated by some time dependent electromagnetic pulse. First, the entire problem space is gridded into a lattice; then, the response is iteratively propagated in time for each lattice point according to Maxwell's time dependent finite difference equations. This technique of solution allows direct modelling of apertures and conceptual simplification of the physics of this problem. The aperture can simply be modelled as a magnetic current source (according to classical aperture theory) and allowed to progressively couple throughout the lattice.

The significance of aperture field penetration will be addressed using the three dimensional, cartesian, electromagnetic coupling code - POLYANA. (W. R. Zimmerman, "User's Guide to POLYANA, Version 1," BDM/A-WRZ-0894-81, February 4, 1981). This code was developed as a general purpose electromagnetic code suitable for determining the EMP (electromagnetic pulse) response or SGEMP (system generated electromagnetic pulse) response of weapon systems in order to insure their shielding effectiveness. The code solves Maxwell's equations using a finite difference technique and a scattered field formulation to determine the field response of a scatterer subjected to incident EMP or source region driven Compton current.

Details of the implementation of aperture sources into POLYANA will be presented along with verification of the modelling procedure. Results of aperture field penetration into a cubical cavity and the resultant cavity excitation will be presented and compared with other numerical treatments. A more realistic scatterer will also be treated. The advantages and limitations of this modelling technique will be given to illustrate its effectiveness.

SIMPLE FOURIER INTEGRAL TRANSFORMS

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The methods discussed in this paper are not new. The purpose of this presentation is to call attention to properties of some simple Fourier integral transform techniques. The term Fourier integral transform (FIT) is used to distinguish these methods from the fast Fourier transform (FFT). There are many situations in the analysis of transient waveforms in which the abilities to use unequally spaced time samples and to specify arbitrary frequencies are preferred over the speed of the FFT.

Numerical Fourier integral transforms are approximations to the continuous, analytical Fourier integral (the FFT is an approximation to the analytical integral too; but, in addition, the FFT is in itself a true transform). The approximation lies in the fidelity of the fit to the transient curve from which a Fourier transform is wanted. Thus a trapezoidal Fourier integral transform calculates the exact Fourier transform of a straight line fit to sample points. Guillemin's technique (1) leads to the same results: the exact Fourier transform of a straight line fit to sample points.

The integration of straight line segments leads most naturally to a summation of line slopes multiplied by the difference between complex exponentials; the Guillemin derivation leads most naturally to a summation of complex exponentials multiplied by this difference between slopes. In both cases, the summation is divided by the square of the angular frequency.

Although both the straight line integration between points and the application of Guillemin's technique lead to identical results, the Guillemin technique formulation is more efficient for general calculational purposes and even lends itself to small programmable calculator computations.

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1. Guillemin, E. A. "Computational Techniques which Simplify the Correlation between Steady State and Transient Response of Filters and other Networks" Proc. National Electronics Conference, 1953, Vol. 9, 1954.

STABLE FINITE DIFFERENCE SOLUTIONS FOR ELECTROMAGNETIC SCATTERING PROBLEMS BY FILTERING THE RADIATION BOUNDARY IN THE TIME DOMAIN MAXWELL EQUATIONS

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Finite difference solutions for scattering problems approximate the radiation boundary in a number of fashions. The approximate treatment of the radiation boundary introduces noise into the problem space which contains the scatterer. The noise generated ultimately causes an instability in the numerical solution of Maxwell's equations. The spatial resolution determines the frequency of the noise generated at the radiation boundary.

A low pass single pole digital filter which operates on the magnetic field components at the radiation boundary effectively limits the generation of noise. The cutoff of the filter is chosen so as to eliminate frequencies above the resolution of the finite difference code. This increases the number of time steps which can be taken before the noise induced instability occurs. This method has been used to stabilize a 3-D code with rectangular spatial cells out to 8000 time steps. In addition, use of the method, results in negligible additional computer memory or run time. The method has been checked against the analytic results of Baum[1] for a perfectly conducting sphere illuminated by a plane wave step function. It has also been checked for a perfectly conducting flat plate illuminated by a plane wave step function.

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[1]Baum, C. E., "The Singularity Expansion Method," Ch. 3 in Transient Electromagnetic Fields, L. Felsen, ed., Springer Verlag, New York, 1976.

NUMERICAL MODELING OF A PRIMITIVE SIEGE SIMULATOR*

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The capability of modeling buried and partially buried wires has recently been added to the Numerical Electromagnetics Code (G. J. Burke, et. al., "An Efficient Numerical Method for Modeling Buried and Partially Buried Antennas", National Radio Science Meeting, Boulder, Colorado, Jan. 1982). This capability will be used to analyze a primitive model of a SIEGE simulator. This model consists of a horizontal wire with voltage source. The ends of this wire terminate on a vertical twin wire transmission line which penetrates the earth to a finite depth. Performance studies of this model will be made as both the simulator and earth parameters are varied.

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*Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

ELECTROMAGNETIC SIGNAL PROCESSING: A TRANSIENT IDENTIFICATION PROBLEM*

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Signals generated from the Lawrence Livermore National Laboratory, Electromagnetic Transient Facility yield a unique set of signal processing problems. The signals are transient in nature, noisy, and cannot be measured simultaneously with the excitation; therefore, the basic identification problem is further complicated.

In this paper we describe various approaches to solving the transient identification problem using existing techniques. We apply algorithms, both recursive (on-line) and off-line, to a representative noisy, transient, electromagnetic signal. The performance of each technique is evaluated using a criterion based on the resulting "fit" of the data set.

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*Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

THREE-DIMENSIONAL COMPUTER MODELING OF ELECTROMAGNETIC FIELDS: A GLOBAL LOOKBACK LATTICE TRUNCATION SCHEME*

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A new lattice truncation scheme for the finite difference time domain approach to the solution of Maxwell's equations has been developed. The problem space is truncated near the sources and the field components on its boundary are generated from those field values known at retarded times on an interior surface one cell from it with an integral representation of the electromagnetic field. The numerical implementation of this global lookback scheme is discussed. Examples which have been used to determine its characteristics and its validity are given.

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*Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

PHASED GAMMA RADIATION-DRIVEN COAXIAL CABLE RESPONSE

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Gamma ray photons interacting directly with electrical cable shields, dielectrics and conductors cause currents to flow into cable loads. The prediction of radiation-induced signals on cables requires a model which properly treats the photon-driven electron transport in the conductor/dielectric geometry, translates the transport into current drivers on the conductors and into transient conductivities in the dielectrics and air gaps, and then propagates the induced current drivers to the cable terminations. Such a model is typically very cable specific and costly to run. We have constructed a simple, approximate model for the radiation transport from which we obtain the current drivers. NET-2 is used to model coaxial cable response to these current drivers. Several effects are included in the model: propagation loss due to transient dielectric conductivity and the effect of cable length on cable response. For example, we present results showing enhanced cable response when the angle of incidence of plane wave gamma radiation is such that phase delay is introduced into the current drivers. Other results will also be presented.

RADIATION RESPONSE OF CABLES WITH RESIDUAL AIR-FILLED GAPS

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The manufacturing process for cables often results in the formation of gaps between the shield and the dielectric which may enhance the x-ray response of a cable. Consequently, attempts have been made to fill the large gaps with a low atomic number dielectric. However, experiments have shown (T. A. Stringer and C. A. Eklund, IEEE Trans. Nucl. Sci., NS-28, December 1981, pp. 4262-4268) that this process is also imperfect and residual gaps of several micron widths persist. The effect of gaps on the x-ray response of a cable has been studied by various investigators and indeed found to enhance the response of a cable (reference above; C. E. Wuller, L. C. Neilsen, D. M. Clement, IEEE Trans. Nucl. Sci., NS-25, August 1978, pp. 1061-1067).

The present work simulates in detail the electrical response, due to an incident triangular pulse of x-rays, of an elemental section of coaxial cable containing residual gaps. The currents in the gaps are modeled with the aid of a 3-D numerical simulation code. Primary electrons are modeled as macroparticles and secondary electrons are modeled with swarm theory. Electron currents injected into the gap are obtained from QUICKE2-M. Various geometrical configurations based on previously reported experimental results (reference 1) are used to represent the gap. Several gaps are assumed to be distributed azimuthally around the cable in the manner proposed in reference 1. The primary electron current in each gap becomes the current driver for an equivalent circuit model for that gap. All the gaps are combined into a single equivalent circuit model for the nonlinear x-ray response of an elemental section of coaxial cable containing air gaps. The total gap currents and short circuit current are calculated as a function of time. The peak short circuit current is presented as a function of photon fluence and pressure for various gap widths and blackbody temperature of the incident photon spectra. A conclusion drawn from these calculations is that, unlike the vacuum case, the cable response with air-filled residual gaps may be less than the response of a perfectly filled cable.

SREMP RESPONSE OF CABLE-LIKE STRUCTURES

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The best method of experimentally investigating the response of a large system to a nuclear surface burst would be to expose the system to an actual burst. This is illegal at the present time. The largest spatial expanse of time-varying air conductivity suitable for source-region EMP research is that produced by bremsstrahlung in the AURORA test cell. This abstract describes a series of short-circuit current response measurements on a number of cable-like extended structures in the AURORA test cell.

A cable-like brass pipe structure was extended from the back of the AURORA test cell toward the AURORA hot spot during a series of AURORA shots. During the shots, current response measurements were obtained for both closed-circuit and open-circuit configurations and for a range of "cable" lenghts. The response of the cable-like structure was interpreted with both an equivalent-circuit technique and a finite-difference code. Implications for simulation of source-region EMP interaction and also for prediction of cable response to source-region EMP will be presented. Similar cable response measurements are planned in March for the electron injection mode.[1,2]

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1 M. Bushell, S. Graybill, K. Kerris, G. Merkel, W. D. Scharf, and D. Whittaker, The Direct Injection of Electron Pulses into Air--A SREMP Simulation Tool, IEEE Proc. Third Int. Pulsed Power Conference, June 1981.

2 M. Bushell, R. Manriquez, G. Merkel, and W. D. Scharf, Simulated Deep Source-Region EMP Coupling to Cylindrical Objects, IEEE Trans. Nuc. Sci., NS-28, No. 6, p. 4457, December 1981.

* This work was sponsored by the Army and DNA under Subtask X990AXVD/EMP Vulnerability Hardening and Testing and Subtask X99QAXVC/EMP Environments and Coupling.

EFFECT OF TRANSIENT RESISTIVITY CHARACTERISTICS
OF METALLIC CONDUCTORS ON SREMP
COUPLING TO UNDERGROUND CABLES

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Previous calculations of source region coupling to underground cables have typically ignored the transient resistivity response of the cables due to the source region excitation. We have self-consistently calculated the response of underground cables to source region excitations utilizing empirical results from exploding wire investigations. It is found that for particular cable parameter domains, transient resistivity effects can drastically reduce the magnitude and time duration of induced currents on underground cables.

SREMP COUPLING TO BURIED CABLES†

- A Linear Modeling Approach -

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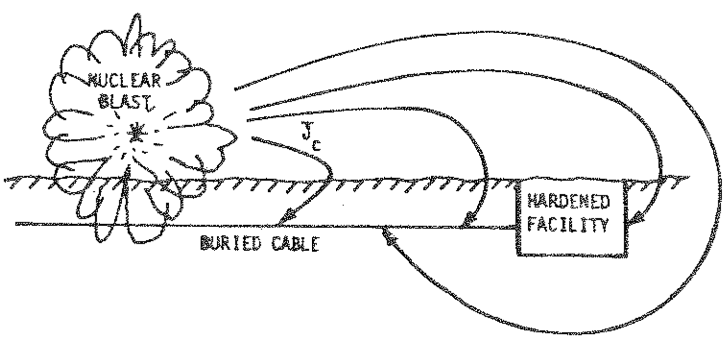
An important problem of current EMP interest is coupling of SREMP fields to buried wires, such as power or communication cables, near hardened facilities as illustrated below. Since the source region of a nuclear weapon is, by definition, highly non-linear, using linear models in the frequency domain is an uncertain procedure. However, for buried cables some non-linearities can be approximated and others neglected, to allow accurate calculations using linear models in the frequency domain. Such a model has been developed for use in parametric studies, since the 1-D and 3-D time domain models require much greater computer run time. The frequency domain and time domain models are shown to compare well over the time range of interest. Maximum energy and charge at the facility can be calculated directly from the frequency domain data, eliminating the need for Fourier transforms to the time domain in many cases.

Another advantage of the linear model is the ease of determining possible breakdown between core and sheath in the cable. The sheath transfer impedance can be used to find internal cable voltage sources resulting from external current excitation. This extension of the outer coupling model was used to calculate inner voltages for typical cables with both SREMP and natural lightning.



†This work was performed under Air Force Contract F04704-80-C-0029E.

CALCULATION OF THE SCATTERING OF A PHOTON PULSE INCIDENT ON A MISSILE AND THE RESULTANT CABLE RESPONSE

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Estimates of the response of a coaxial cable to an external pulse of photons requires determining the hardening of the pulse spectrum due to shielding materials around the cable as well as determining the effect of the photons on the cable itself. For a missile, it is simplest to assume the cable lies along the axis of the missile and to include the missile skin as an annulus around the cable. More complicated geometries, including shadow shielding by the missile components, must be considered ultimately but this basic problem contains all of the elements of the more sophisticated calculations and provides a check on the calculational techniques used in the latter.

A computer analysis of the shielding resulting from this simple configuration was performed using the MORSE multigroup Monte Carlo transport code. The cross sections used in the transport calculation were generated with the GAMLEG code. The MORSE code permits three-dimensional geometry specification and accounts for photon scattering, attenuation, and secondary particle production. The cross sections include Compton scattering and photoelectric absorption. The transport calculation provides the fluence and energy spectrum of the photons penetrating the missile skin and striking the cable.

The photon spectrum obtained in the above analysis is taken as input to QUICKE 2-M to calculate electron yields from the cable shield as a function of total fluence and blackbody temperature of the photon source. The resulting current is then taken as the driving current source in an equivalent circuit model to obtain the photon induced cable response. The short circuit current is presented as a function of fluence and blackbody temperature for an incident photon pulse which is triangular in time. This response will be compared with the response of the cable in absence of the missile.

Withdrawn

SOURCE-REGION EMP PENETRATION THROUGH APERTURES

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Abstract

The source region EMP penetration through a hatch aperture at one end of a flanged cylinder is analyzed. The penetration is characterized by the open circuit voltage induced across the hatch gap. The quasi-static approximation is used. The results are presented by means of simple circuit diagrams.

EFFECT OF CORONA ON EMP INDUCED WIRE CURRENT*

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ABSTRACT

A simple model is developed to describe corona formation due to EMP incident upon a finite long wire. The corona model is then used to derive approximate transmission line equations for the EMP induced current and voltage. Based on simple analysis and numerical solutions, we concluded:

1. Without taking into account the effect of electron attachment and space charge dynamics, the simple approximate model leads to an equivalent transmission line and provides an upper bound to the corona effect in its reducing EMP induced wire currents and voltages. In particular, for the typical cases considered (wire length 1200 meter, radius 2 mm, altitude 10 km), we estimated

$$I_{max}^{corona} \Big/ I_{max}^{no\ corona} \gtrsim 1/40 .$$

   The ratio depends on θ (angle between wire and incident wave) and σ_{max}: becomes closer to 1/40 at smaller θ and larger σ_{max}.

2. The "worst-case" incidence angle θ, for the $I_{max}^{corona}(\theta)$, is reduced from $\sim 15°$ to $\lesssim 10°$ and then disappears as the conductance g increases from 0 to $\gtrsim 10^{-6}$ mho/m and the σ_{max} increases from 0 to $\gtrsim .2$ mho/m.

3. Lower frequency coupling is damped by the corona relatively more than higher frequency does, as evidenced by the relatively shortened time span for I^{corona} compared to $I^{no\ corona}$.

4. The bounding mechanism for the corona effect, a balance between more EMP coupling to aircraft due to equivalently thicker wire and less coupling due to corona conductance loss, is reduced down to one parameter, σ_{max} (or n_{max} of electron density). Its self-consistent dynamic determination is needed to obtain further detail of the corona effect.

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*Research sponsored by Air Force Weapons Laboratory, Albuquerque, New Mexico.

NUMERICAL AND ANALYTIC SOLUTIONS FOR RADIATION INDUCED DIELECTRIC CONDUCTIVITY

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Dielectric materials irradiated with x-rays or γ-rays exhibit a measurable induced conductivity. This effect is important in the study of the electrical behavior of materials used in missiles that may be exposed to nuclear radiation environments. Simplified solid-state models have been used by various investigators to study this effect. Analytic and numerical solutions have been obtained for rather restricted conditions.

The present study is based on the works of Fowler (Proc. Roy. Soc. A236, 1956, pp. 464-480) and Weingart et al. (IEEE Trans. Nucl. Sci., NS-19, Dec. 1972, pp. 15-22). A set of rate equations governing the time dependence of conduction and trapped electrons is solved analytically and numerically for a triangularly shaped (in time) pulse of x-rays. Our approach differs from that of Weingart et al. in that allowance is made for complete filling of trapping levels and that a wide range of ionizing conditions is considered, i.e., low to high doses and dose rates. Analytic results have been obtained by dividing the time domain into seven intervals, each characterized by different conditions which permit approximate equations to be developed. The analytic approach facilitates interpretation of the results in terms of dominant physical processes in each of the seven intervals. A numerical approach was adopted which effectively solves the set of stiff differential equations forming the model. Prompt and delayed conductivity were calculated as a function of time for polyethelene and teflon over a wide range of doses and dose rates. Approximate formulas of the form $\sigma_p = F\ (D)\ \dot{\gamma}$ were developed for the prompt conductivity σ_p, where F (D) is a nonlinear function of dose D and $\dot{\gamma}$ is the dose rate. The numerical simulations reveal that a single exponential can not be used to represent the delayed conductivity for all times.

THE DISCHARGE CURRENT IN THE LIGHTNING RETURN STROKE*

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The current in the lightning return stroke has been the object of a number of analytical models of increasing complexity. Bruce and Golde introduced the concept of a velocity of current pulse propagation. Later, Dennis and Pierce introduced the concept of a traveling current wave along the leader channel. In each of these and later papers, however, the current pulse amplitude, pulse shape, and velocity are assumed functions.

In this paper, we develop a nonlinear, nonuniform transmission line model to find the velocity of current pulse propagation, the current amplitude, and current rise time as functions of time and therefore height. The flexibility of a transmission line model allows us to include physical variables in the form of resistance, inductance, capacitance, and conductance per unit length as functions of height and the history of the current flow through a given cross section of the return stroke channel. Only resistance per unit length is treated in a nonlinear fashion here. The remaining variables are assumed constant to reduce the complexity of the model.

The resistance per unit length is determined by the evolution of a complex hydrodynamic model, which calculates physical and electrical parameters of the channel plasma as functions of time and radius for each cross-section of the plasma. The resistance of a unit length of plasma channel is then found by integrating the conductivity over radius. This resistance per unit length is then updated in the transmission line code at each time step. The transmission line solution has as an initial state the sudden closing of a high voltage switch about 100 m from the ground. The evolution of the current and voltage waveforms along the channel then determine the current pulse rise time, the velocity of the current pulse propagation and the current amplitude. Necessary initial conditions for a propagating pulse are also shown.

*Work performed while at Cooperative Institute for Research in Environmental Sciences, Boulder, Colorado.

ELECTROMAGNETIC PULSE EMITTED BY LIGHTNING

- experimental data and mathematical models
- natural and triggered lightning strokes.

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In this communication we present our work to date, experimental as well as theoretical, on electromagnetic fields emitted by lightning, both natural and triggered.

The National Research Center of Telecommunications (C.N.E.T.) for several years has been working to deepen its understanding of emitted Electro-magnetic pulses by return-strokes and leaders both in the context of the Saint-Privat d'Allier station experiments and more recently by participating in the COPT 81 campaign (Tropical Deep Convection).

For the experimental programm, and for the studies of the strokes, triggered as well as natural which band sensors (150 Hz - 20 MHz) or spectral analysis (60 MHz - 1 GHz), has been used associated with rapid data acquisition systems.

In parallel, theoretical modelling of this emitted field by the return stroke was carried out, taking into account the current wave-form the upward velocity, the ground resistivity and the height of the observation point.

Finally, we present preliminary results of the C.O.P.T. campaign both wide band and harmonic analysis, on esssentially intra-clouds events.

LIGHTNING ACTIVITY CHARACTERISTICS FROM VHF SPACE-TIME MAPPING

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A wide band VHF system employing time difference of arrival techniques has provided azimuth and elevation angles to individual sources of electromagnetic impulses radiated from lightning discharge processes. The simultaneously observed directions and times of arrival recorded at two stations separated by several tens of kilometers define the three dimensional location of each source as a function of time. Analysis of data has revealed characteristics of the lightning discharge process from several storms and has allowed us to accurately associate lightning activity with storm reflectivity and internal wind structure obtained from Doppler radar data. Recent results of this work include: (1) the space-time structure of lightning discharges is extremely complex; (2) lightning activity is generally located in close proximity to, but not necessarily within, the high reflectivity regions of storms; (3) the average height of VHF sources is 4-5 km for cloud-to-ground (CG) flashes and 5-6 km for intracloud (IC) flashes, where the temperature is between -5° to $-20^{\circ}C$; (4) VHF sources for CG's and large IC's seldom exceed 10 km height; (5) a new class of small IC's forming a canopy over the main updraft region of a storm produce almost a continuum of lightning activity centered at 12-13 km height; and (6) lightning activity moves in a broad front through the thunderstorm volume at progression speeds between $2x10^4$ and $2x10^5$ $m \cdot s^{-1}$.

AIRBORNE MEASUREMENTS OF LIGHTNING-INDUCED CURRENTS

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INTERPRETATION OF IN FLIGHT LIGHTNING DATA

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One of the current topics having a great deal of interest within the lightning community is the interaction of lightning with aircraft. One of the biggest unknowns in this area is the knowledge of the lightning environment at aircraft altitudes.

In order to obtain such data, NASA Langley Research Center has instrumented an F-106 to obtain electromagnetic coupling data during a lightning event. Data for both attached and nearby strokes have been obtained. The data consists of derivatives of the normal electric field and the tangential magnetic field measured on the external aircraft skin.

In this paper, the problem of determining the lightning characteristics from the aircraft data is discussed. That is, the aircraft response is "backed out" of the data such that the incident current or LEMP waveform is inferred. Results are given for both cases, and are consistent with current knowledge of risetimes and channel current.

Laboratory Model of Aircraft-Lightning Interaction and Comparison with In-Flight Lightning Strike Data

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Modeling studies of the interaction of a delta-wing aircraft with direct lightning strikes have been carried out using an approximate scale model of an F-106B. The model, which is 3 feet in length, is subjected to direct injection of fast current pulses supplied by wires, which simulate the lightning channel and are attached at various locations on the model. Measurements are made of the resulting transient electromagnetic fields using time-derivative sensors. Small B-dot and D-dot sensors have been placed on the model in the locations corresponding to their actual locations on the N.A.S.A. F-106B (1). The sensor outputs are digitized with a sampling interval of 50 ps for a total time of 20 ns, which is the clear time of the apparatus. The signal-to-noise ratio, defined as the peak signal divided by the RMS noise, is more than 40 dB. The noise level is reduced by averaging the sensor output from 10 input pulses at each sample time.

The B and D waveforms show the input pulse followed by reflections due to the various parts of the model structure. These reflections die out quickly, typically within 20 ns, and are explained roughly in terms of simple transmission-line arguments. Computer analysis of the measured fields includes Fourier transformation and the computation of transfer functions for the model. The transfer functions show several resonances of moderate Q. These include the half-wavelength resonance of the fuselage and several higher frequency resonances.

Comparisons of these transfer functions with spectral amplitudes computed for in-flight data show good agreement regarding the frequencies of the resonances. However, one in-flight D-dot waveform shows a strong fuselage resonance (8 MHz) which has a larger Q than that apparent in the corresponding transfer function. This is indicative of a lightning channel for this particular in-flight event with a higher impedance than the wires on the model.

The basic technique has the potential for investigating the response of other types of aircraft and studying interior as well as exterior fields.

1. Pitts, Felix L., "Electromagnetic Measurement of Lightning Strikes to Aircraft," AIAA 19th Aerospace Sciences Meeting, St. Louis, MO, January 1981. AIAA 81-0083.

IMPROVEMENTS IN THE ANALYTICAL TREATMENT OF SOURCE REGION EMP

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The approximate analytical solution to Maxwell's equations in the nuclear source region presented by Crevier and Pettus[1] has been extended from the wave phase into the diffusion phase in the code MODELC. This was done by including terms for the transverse Compton current, the conduction current and the outgoing wave (G). Inclusion of these additional terms required modification of the previous equations, and also necessitated use of different numerical techniques for solving the new set of equations. The accuracy of this code during periods of high conductivity was further enhanced by including a finite conducting ground through the use of Conrad Longmire's universal soil impedance concept.

The modification to the basic equations presented by Crevier and Pettus and the implementation of the conduction current are shown here along with comparisons between this code and the 2-D finite difference code LEMP. In addition, the sensitivity of the solution to different formulations of Maxwell's equations will be discussed.

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[1] Crevier, W. F. and E. Pettus, "Approximate Methods for Calculating Early Time EMP from Surface Bursts at the Ground in, and Near, the Source Region." IEEE December 1979.

This work was supported by the McDonnell Douglas Astronautics Corporation under Contract Number MDAC 81725031.

CURRENT RESEARCH IN HAEMP ENVIRONMENT PREDICTION: ROUND-1 CODE

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A comprehensive new one-dimensional computer code, ROUND-1, for predicting high-altitude burst gamma-induced electromagnetic pulse (HAEMP) has been developed at Harry Diamond Laboratories (HDL). The code is designed to unify up-to-date early-time and late-time technology into one convenient framework. Several one-dimensional approximations to Maxwell's equations are incorporated as available options. These include the "congruent ray" (CR) model (proposed by Wyatt in 1971) and "vertical ray" (VR) model (viz., Longley and Longmire's CHAP code[1]). The CR model incorporates as a special case the "far-plane" model.[2] Both CR and VR models incorporate as special cases the "high-frequency" model of Karzas and Latter[3] amd Longmire.[4] Spherical geometry is used throughout. Early-time Compton drivers may optionally be computed self-consistently. First and second gamma scatters are obtained analytically, and associated Compton currents and ionization are obtained by "particle-pushing" at early time or by "particle displacement" at later time. Third and later gamma scatters and associated currents and ionization are obtained from a companion Monte Carlo gamma transport code using data smoothing and fitting algorithms. An innovation of potential interest at early time is optional computation of nonequilibrium temperature of conduction electrons, with air chemistry dependence on electron temperature instead of on electric field strength.

Current work is directed toward (1) treatment of late-time interaction between the ground and the high-altitude source region by shifting the center of retarded time from the burst to the image point of the burst beneath the ground and adding a ground mesh; and (2) a three-ray version of the CR model in order to estimate three-dimensional perturbations of the one dimensional approximation.

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[1]Longley, H. J., and C. L. Longmire, Development of the CHAP EMP Code, Defense Nuclear Agency, Report DNA 3150T, 7 Nov. 1973.
[2]Longley, H. J., Robert M. Hamilton, and C. L. Longmire, Development of the LHAP-2 EMP Code, MRC-IR-77-409, Dec. 1977.
[3]Karzas, W. J., and R. Latter, Phys. Rev., Vol. 137B, p. 1369, 1965.
[4]Longmire, C. L., Close-In EM Effects Lectures X and XI, Los Alamos, Scientific Lab., Report LAMS-3072, April 1964.

AN INTRODUCTION TO EMP CALCULATIONS USING A NONEQUILIBRIUM ELECTRON DISTRIBUTION FUNCTION

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In EMP calculations, it is assumed that the electron distribution function (EDF) is in equilibrium. If the electric field at $\underline{r}$ and t is $\underline{E}(\underline{r},t)$, then it is assumed that the EDF is that of an electron gas which has come to time equilibrium under the influence of a time-independent electric field with the same magnitude as $\underline{E}$. This makes it possible to write the average electron energy density U and drift velocity as a function of E/p, and, consequently, the momentum transfer and energy exchange collision frequencies as functions of E/p and thus U. However, if the time to reach equilibrium is sufficiently long, the electric field of the EMP may change by a large fraction before EDF equilibrium is achieved. The EDF is then in a state of nonequilibrium and the collision frequencies are no longer functions of U.

This paper is an introduction to nonequilibrium EDF EMP calculations. We assume that the EDF can be written as $f(w,\theta,t) = f_o(w,t) + f_1(w,t)\cos\theta$, where w and θ are the magnitude of the position vector and polar angle in velocity space with $\underline{E}$ being directed along the polar axis. Then it will be shown that the Boltzmann equation may be solved analytically for f_o and f_1 in the case of a simple collision model consisting of electrons and molecules treated as hard spheres and the electric field given by a unit step.

With these quantities in hand, this paper illuminates some of the issues associated with a nonequilibrium EDF. For example, the swarm equation for U has been used to calculate the time required for build-up of U from a thermal value to a final value due to a unit step function E. But use of this equation assumes that the energy exchange collision frequency is a function of U even though during this time the EDF cannot be in equilibrium. Thus, an error is introduced. This error may be estimated by calculating U(t) directly from the EDF and comparing this result with that derived from the swarm equation for U with the energy exchange collision frequency derived using the simple collision model.

RADIATION SOURCES FOR LATE-TIME HIGH-ALTITUDE EMP

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Results of recent analysis of neutron-induced sources for the late-time high-altitude EMP will be discussed. These results include outputs of detailed coupled neutron-gamma Monte Carlo analysis for prescribed energy neutron sources. Characteristics of the resulting EMP source terms will be described.

AN APPROACH FOR ELECTROMAGNETIC VALIDATION TESTING OF LARGE FACILITIES

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Periodic validation of the EMP hardness of a large facility is an existing requirement for many DOD agencies. Frequently, the time and cost to perform this validation with high level pulse simulators are prohibitive. In addition, these simulators are usually not transportable and installation of the few that are can greatly impact the site and facility being tested.

There is another technique that has been utilized that involves minimum cost, time, and facility impact. This approach uses CW illumination techniques and involves excitation of the facilities' major apertures and conductive penetrations. This technique generally supplements an analytical hardness assessment effort to reduce some of the analytical uncertainties.

This paper describes some of the CW illumination approaches used in EMP hardness validation programs.

*This work was performed under Air Force Contracts F29601-78-C-0033 and F29601-80-C-0036.

TOWARD AN INCREASED UNDERSTANDING OF AIRCRAFT EXTERNAL RESPONSES IN SIMULATOR FIELDS*

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A review of the external currents and charge density responses, as measured in the HPD/VPD II simulator during the system level test on the A-7E and F-14A, will be presented. The pertinent features of the response spectrum will be identified and briefly discussed. Then a comparison will be made between the peak values of the response spectrum, the theoretical predictions of MoM and THREDE codes, and scale model data.

The primary purpose of this paper is a discussion of the external responses due to variations in the configuration and orientation of the aircraft. Particular emphasis will be placed on developing a conceptual model to explain the redistribution of the currents on the surface of the aircraft due to the presence of a ground plane. The conceptual model used to explain the observed phenomena will be supported by analytical calculations.

Finally, the impact of current redistribution due to configuration/orientation variations on system level test planning will be briefly discussed.

* This work was sponsored by the Defense Nuclear Agency under Contract DNA001-81-C-0093.

A METHODOLOGY FOR THE USE OF THRESHOLD DETECTORS IN SYSTEM LEVEL TESTING AND ASSESSMENT

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Military Systems exposed to nuclear EMP may suffer component failure and/or logical upsets. In order to determine a systems vulnerability to EMP Threat, a combination of analysis and test is usually required. Analyses typically have large uncertainties, therefore, actual test data is required to obtain high confidence results. Testing, on the other hand, has proved to be expensive and time consuming. Also, using conventional EMP testing techniques, it is very difficult to perform a 100 percent sample survey of mission-critical pins under all configuration conditions and incident wave orientations for most large systems.

In order to quickly and completely sample system responses, a method is needed to allow for hundreds of measurements per day instead of the present 20-30 per day. Threshold detectors are available to enable fast screening of a system. The Threshold Detector (TD) is a wide band, peak signal responding device that is small, accurate, self contained, and relatively inexpensive.

This paper describes a method using these TD's, in conjunction with conventional testing techniques, to enable large scale surveys to be accomplished with high confidence, low risk and minimal test time.

CABLE CURRENT INJECTION TESTS OF A
MAGNETIC TAPE UNIT

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This paper reports initial results in a new bulk cable current injection test facility. The MITRE Corporation has assembled and is operating a small cable current injection EMP Simulator facility to test the EMP hardness of electronic equipment which the Air Force Electronic Systems Division may install on the E-4B Advanced Airborne Command Post. The first piece of equipment to be tested was the MU-688 magnetic tape unit, which was exercised during testing by connecting it to a UGC-129 teletypewriter. The range of frequencies available varies from approximately 10 kHz to 100 MHz and the current is variable from 10 ma to 10 amp. The injection mode is to drive the interconnecting data cable bundle and ground plane with a variable mutual inductance loop which is excited by a simple 0-10 KV spark-gap pulser. Single pulse and up to 2 pps modes are available. Coupling to shielded leads will be compared to analytical model results. The paper will be unclassified.

+Supported by the U.S. Air Force Electronic Systems Division, Bedford, MA 01730

TIME DOMAIN INSTRUMENTATION FOR EMP MEASUREMENTS

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The nuclear electromagnetic pulse (EMP) is a very fast risetime, high amplitude signal which can strongly couple into electronic systems and has great capability for damage to electronic components, especially integrated circuits and computer circuits. As a consequence, systems such as airplane, missiles, ships and communications centers are increasingly being tested for EMP vulnerability. Such vulnerability tests consist of subjecting the system to the threat level, time domain EMP field in a suitable EMP simulator driven by a high voltage pulser. This will vary from a full system such as an airplane or a ship down to the box or even component level. The EMP pulses may consist of single shots many minutes apart (high-level) or repetitive pulses at the rate of thousands per second (low-level). Data recording systems have been developed which can record various electromagnetic field and system response data in a flexible and efficient manner.

Automatic transient data systems are described which require little operator intervention and not only automatically set up instumentation, but also provide sequenced control of EMP pulsers. Remotely controlled wideband fiber optic and dielectric waveguide microwave analog telemetry links provide electrically isolated signal transmission paths from the "noisy" simulated EMP environment back to the "quiet" recording instrumentation area. These links may contain internal attenuators, baluns, calibration generators and integrators. Ground plane reference sensors are typically hardwired with low-loss coaxial cable directly to the instrumentation system with cable compensation units added to correct for high frequency rolloff. The transient data system also includes special equipment, such as loss active signal splitters and programmable trigger delay units to provide recording instrumentation inputs. Software in the data system automatically calibrates the telemetry links and corrects the recorded data for signal path component transfer functions and provides a final time-tied output in engineering units.

A NEW GENERATION OF SMALL CURRENT PROBES FOR EMP TESTING

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Wideband Current Transformers

Current transformers are widely used in the EMP community as a measurement device. We will present the general theory of current transformer operation and address differences between ideal and real current transformer performance. The real tansformers exhibit resonances and other effects which appear to be transmission line phenomenon. Bandwidth limitations will be considered, and methods suggested for extending the bandwidth. Finally, a brief summary of our experimental results will be presented.

Several current probes made for EMP testing will be presented. These include the Clamp-On Current Probes (CCP) and Clip-On Probes (COP) which have been successfully used in recent test programs. Bandwidth and pulse fidelity data will be presented for these probes.

A 400 MHZ CURRENT BREAKOUT PROBE FOR HIGH ATTENUATION SHIELDED CABLES

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There is an increasing emphasis being placed on obtaining highly accurate and precise transient measurements on individual signal wires for EMP testing of highly shielded test objects. The accuracy requirements are generated from the need to obtain precise data for EM coupling model validation. In addition, coupling information obtained at frequencies higher than those generally specified for EMP testing (i.e., greater than 100 MHz) is useful for extrapolating to other environments such as SGEMP and EMC. Test point locations which do not allow simple access inside the innermost shielding layer must be accessed externally with minimal perturbation to the shielding topology and shielding effectiveness, and allow efficiency for reconfiguring to other test points.

A breakout current probe has been developed at The BDM Corporation which will be used in EMP testing and which meets the above design criteria. During previous EMP tests, empirical data was obtained on several varieties of breakout probes designed for similar usage. It was clear that stray lead inductance and capacitance would have potentially adverse effect on probe performance at higher frequencies. A model was developed and validated which predicted the key parameters that required precise control and the limits on those parameters required to assure optimal performance. In addition, the qualities of earlier probes which assured efficient reconfiguration, minimal internal crosstalk, and a high level of overall shielding effectiveness were incorporated in a prototype design. The increased high frequency response requirements were met by using coaxial windings on a ferromagnetic core.

The prototype probe was designed and built. It demonstrated an essentially flat response from about 100 KHz to over 400 MHz with a transfer impedance of 5 to 10 ohms depending on the core material used and the number of windings. Crosstalk data will be provided which demonstrates that the limiting component is the cable connector. Shielding effectiveness curves will be provided which show that the probe is in excess of the nominal 80 dB required by specific test requirements. Design details will be discussed.

PRACTICAL PROBLEMS OF FIBER OPTICS IN FIELD APPLICATIONS

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Fiber optics has found application in countless commercial and industrial environments where its various attributes may be used to advantage. However, in field applications where the fiber must tolerate a large amount of handling and abuse and where connections are mated and demated repeatedly, careful selection of materials must be made to assume an acceptable mean time between failures. This presentation discusses the various elements of a fiber optic system (fiber, connectors, etc.) intended for field use. The application is approached exclusively from a practical point-of-view with little theoretical treatment. General first-hand observations of fiber optic performance at EMP sites such as Trestle and HPD (AFWL) are presented. Several of the more serious fiber optic problems that were encountered are discussed complete with the various solutions that were tried. The effectiveness and tradeoffs of the solutions are discussed. Briefly, a general overview of present capabilities is offered with a few predictions of what future systems might be expected to achieve.

A FIBER-OPTICALLY-CONTROLLED WIDEBAND SWITCH FOR MULTIPLEXED DATA ACQUISITION IN EMP TESTS

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The basic design of a fiber-optically-controlled switch will be discussed. The switch, which is designed for use in SGEMP/EMP environments, uses a combination of fiber optics, microprocessor and Stripline Technologies to perform the switching task in a wide bandwidth and low-power manner.

The basic design of the switch allows multiple switches (up to 8) to be controlled from one controller through one pair of optical fibers and an optical splitter. In addition, the communication format allows for the control of wideband data links as well as control of integrators and accessary equipment.

AN INSTRUMENTATION SYSTEM FOR GREATLY INCREASING THE DATA COLLECTION RATE OF EMP-INDUCED WIRE CURRENT MEASUREMENTS IN AIRCRAFT

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EMP assessments in modern military aircraft require that hundreds or even thousands of internal wires be measured for induced current transients. An instrumentation system has been developed which allows for a nominal sixty-four such measurements to be made in any given day of testing without requiring access to the aircraft. Reconfiguration is then performed during non-testing periods of the day.

The heart of this system is a Remote Coaxial Switch (RCS) (2) which connects eight current probes, one at a time, to a wideband analog fiber-optic data link for transmission to a Data Acquisition System (DAS). Typically, eight such switches and data links are utilized simultaneously by a DAS so that sixty-four current probes can be interrogated, eight at a time. Each RCS is set to the desired probe remotely via a fiber optic control link. Switch positions on up to eight different RCS units are set from a control unit, which also displays verification status.

The system also uses a new type of Clip-On Current Probe (COP) which greatly eases the chore of instrumenting the aircraft.(3) Probe verification and system integrity are tested in the frequency domain using a network analyzer so that noise shots are not required during testing with the pulser.

Measurements made on a test aircraft indicate that the effect of adding the switch and seven other current probes to test wires does not appreciably affect the current measurement. This effect is less than is the perturbation of the wire current by just one probe and data link,(1) at least for instances where all of the probe cables are of length one meter or less.

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(1) W.J. Motil and G.D. Sower, "Instrumentation Effects Upon EMP Induced Wire Current Responses in Aircraft", NEM 1982.
(2) G.D. Kahn, "A Fiber Optically Controlled Wideband Switch for Multiplexed Data Acquisition in EMP Tests", NEM 1982.
(3) S. Cave and G.D. Kahn, "A New Generation of Small Current Probes for EMP Testing", NEM 1982.

* This work was performed under the following Defense Nuclear Agency Contract: DNA 001-80-C-0177.

CONCERNING THE SCIENTIFIC BASIS FOR NOISE AND INTERFERENCE CONTROL

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Complex electronic systems can be vulnerable to various kinds of electromagnetic environments. It is a very challenging task to have a detailed understanding of all the resulting signals at all places of importance in the system. In order to control these signals and bring them all below some particular levels with a high confidence, it is necessary to have some general techniques to control the electromagnetic interaction with the system as a whole and reduce the number of critical variables which govern the system response. To begin this discussion of the scientific basis for noise and interference control one can consider three basic ideas which are not totally independent: electromagnetic topology, symmetry, and orthogonality.

Electromagnetic topology has both qualitative and quantitative aspects. The qualitative side includes the hierarchical volume/surface topology and the equivalent dual graph or interaction sequence diagram. This aspect leads to design guidelines for shielding penetratons and discrete shielding concepts which involve combinatoric considerations. On the quantitative side one begins with the BLT equation for signal transport through the system and partitions the terms according to the hierarchical topology to form supermatrices and supervectors with special properties. Assuming effective shields and subshields one obtains the good-shielding approximation as an approximate solution to the BLT equation. Combining this with norm concepts gives bounds on signals in the various system layers. This gives a format for specifying the performance of the important elements controlling the electromagnetic penetration.

Geometrical symmetries, such as a symmetry plane, can be used to decompose the system response into terms which respond in different ways to the electromagnetic excitation. By imposing corresponding symmetry conditions on the exciting field certain undesired response terms can be suppressed. A simple example of this concept is cross polarization.

One can think of orthogonality in a simple form as two vectors at right angles to each other as in cross polarization. However, one can more generally think of orthogonality by extending the concept of dot product to symmetric product involving integration of dot products of vector functions over various domains. Since such symmetric products appear in modal coefficients (both eigenmodes and natural modes) then orthogonality is interpretable as zero modal coefficients which provides an alternate interpretation of the use of symmetry to cancel certain responses. Furthermore shielding as used in electromagnetic topology can be interpreted as making coupling coeefficients to internal modes small giving a concept of "approximately orthogonal".

APPLICATION OF SHIELD TOPOLOGY TO SYSTEM PROTECTION

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The protection of electronic systems from strong external sources of electromagnetic stress such as lightning and the EMP, requires a systematic application of closed electromagnetic barriers between the source and the protected circuits. Because systems are often constructed by integrating packaged electronic equipment and subsystems into airframes, ships, or ground based facilities, the protection is usually allocated between a system level barrier and an equipment level barrier. In this paper we discuss some implications of the choice of circuit threshold, of the ability to test or evaluate the protection, and of the ability to specify thresholds on the procedures for allocating barrier effectiveness.

The system barrier must at least reduce the stress applied to the protected circuit to below the damage level, but there is no benefit from barrier improvement that reduces the threat stress to much below the stress that the system itself generates during the normal operation. The use of damage as the threshold for unsatisfactory performance is contingent upon the damaged condition being accurately defined. However, only the functional (and not the damage) characteristics of devices are usually carefully controlled. Hence the damage threshold often cannot be accurately defined, and sometimes may vary over several orders of magnitude among different lots or different manufacturers of functionally interchangeable parts. Furthermore, the damage threshold can rarely be determined without destroying the unit being tested.

The ability to specify and test a barrier is affected by the shape, size, and complexity of the barrier, as well as by the threshold. More accurate source simulation or more thorough analysis are required to evaluate barriers having many arms, branches, or extensions than to evaluate barriers of simple shapes such as cubes or spheroids. In addition, since for every n penetrating conductors there are n^2 modes of excitation, the choice of a barrier surface that minimizes the number of required penetrating conductors will also make specifications and evaluations of the barrier (or equipment immunity) easier. Since damage in general implies nonlinear behavior, the specification and evaluation of the equipment level barrier is further exacerbated if the damage threshold is chosen, because then either the nonlinear behavior of the equipment must be well understood, or the details of the threat and its interaction with the system level structure must be thoroughly understood, if confidence in the evaluation of the nonlinear events is to be gained.

USE OF TOPOLOGICAL DECOMPOSITION CONCEPTS FOR DETERMINING EMP HARDNESS ALLOCATIONS FOR MULTI-SHIELDED SYSTEMS

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ABSTRACT

Topological shielding concepts may be applied to the design of an EMP hardened system in order to insure that the shielding design is consistent and that the chances of a shield failure are minimized. A topologically consistent design requires that all electromagnetic shields within the system be closed, and that all penetrations into a shielded region be provided with some form of EMP protection.

In carrying out a design for a particular system, it is desired to use a balanced hardening approach. This implies that the levels of EMP protection at each penetration point within the topological layers are chosen in such a way so that the responses within the system are comprised of roughly equal contributions from each POE.

The topological decomposition of a system permits the determination of the appropriate amounts of required hardness at each POE. This is known as developing hardness allocations for the system. Often, this process is carried out by considering only one class of penetrations, and neglects the effects of the others. For example, a shielded enclosure is frequently described in terms of a "shielding effectiveness" for incident electromagnetic fields, neglecting the effects of conducting penetrations which usually contribute substantially to the internal response.

This paper will review the topological concepts of shielding, and illustrate how they may be applied to a groundbase system. Special attention will be paid to the methodology of developing a rational scheme of EMP hardening allocation at the various POEs in the shielding topology.

SOME ASPECTS OF EMP SPECIFICATIONS

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Specifications form one tool in the overall process of establishing/achieving/validating that a system is hard to EMP. Requirements that specifications must satisfy in order to serve different purposes in the overall hardening process will be discussed. Issues to be covered include

- Quantities to be used in specifications
- Locations in a system where to apply specifications
- Subsystem versus system-level specifications
- Specifications and hardness validation schemes

The use of existing system-level EMP test data in defining specifications is also discussed.

TRANSPORTABLE EMP SIMULATOR EMIS-3

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EMIS-3 has been designed and constructed for the study of EMP effects on large systems such as communication centers, ships and aircraft. It is a transportable, sub-threat-level, radiating system consisting of one 0.5 MV pulser with three different antennae. The radiating part is a vertical cone VPD (vertically polarized dipole), a horizontal "dipole" HPD (horizontally polarized dipole) or a system called HYBRID because it is a hybrid of a radiating and a bounded wave system.

The VPD and HPD antennae can be situated together near the object under test. The pulser must be moved from one antenna to the other. The HPD can be rebuilt to the HYBRID and vice versa.

The VPD has a wire-cage flared cone above a ground plane with a height of 20 m and a diameter at the top of 35 m. The cone is resistively loaded.

The HPD consists of a wire-cage cylinder with a diameter of 5 m and a height of 20 m which is center-fed by the pulser via a bicone. Each end of the cylinder is tapered to ground and terminated by a resistive load. The total length is 110 m, but can be extended to more than 300 m.

The HYBRID consists of an elliptically shaped wire-cage cylinder with a diameter of 5 m and height of 20 m which is resistively loaded. The pulser is situated in the center and connected to the cylinder via a bicone. Each end of the cylinder is connected to ground. The total length is 60 m.

The performance and design characteristics of the simulator will be presented.

LOW FREQUENCY SPECTRUM CONTENT ASSESSMENT FOR VERTICALLY POLARIZED DIPOLE TYPE SIMULATORS: FIRST ZERO CROSSING TIME VS. DAMPING RATIO

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Vertically polarized dipole type simulators such as the VPD II can be characterized, at least approximately, by a radiating dipole antenna with a tapered resistive loading [1]. The radiated far field arising from a step function excitation at broadside (figure 1) shows a damped, periodic behavior. This type of behavior is not unexpected. Mathematically, it can be shown that the simulator current behaves as an infinite series of damped oscillators of frequency

$$\omega_n = \omega_n^{real} + i\omega_n^{imag} \qquad n = 1,2,3,\ldots$$

where the damping ratio $\omega_n^{imag}/\omega_n^{real}$ increases (more damping) with δ where δ is a measure of the transmission line loading per unit length, Z', i.e.

$$Z' = \frac{2Z_{\infty}\delta}{h-\zeta}$$

where Z_{∞} is the dipole characteristic impedance, h is its height, and ζ the position along the dipole.

The lowest frequency oscillator is the most strongly excited, typically, and is predominant in determining the low frequency spectrum content. When critically damped, the spectrum is uniform from the lowest frequencies to the reasonant frequency of the lowest frequency oscillator, a nearly ideal situation. Note that in figure 1 when the damping is increased, the zero crossing time decreases. It is evident that zero crossing times provide an incorrect means of assessing a system's low frequency content. In fact, increasing zero crossing times of a particular facility can diminish the relative low frequency content.

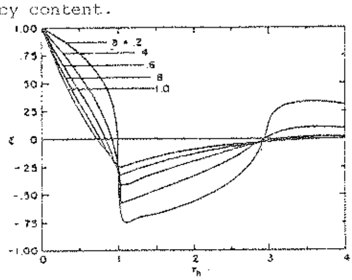

Fig. 1. ξ versus τ_h for δ = 0.2, 0.4, 0.6, 0.8, 1.0.

[1] Wright, D. L. and Prewitt, J. F., "Radiating Dipole Antenna with Tapered Impedance Loading," IEEE Transactions on Antennas and Propagation, November 1975

ABSTRACT

Spectral Notches in EMP Simulators, Their Effect on System Responses, and Data Evaluation Methods*

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Notches of a sinc-function nature are found in practically all EMP simulator spectra. Their presence is regarded by many as deficient in that excitation of resonant system responses at the notch frequencies will be too low or nonexistent.

The phenomena are treated as time-domain superposition effects of the fields in the test volume with the resulting constructive and destructive superposition of the resonant responses. The key point of the analysis is that at the notch frequencies simple resonent responses go through at least their first two half cycles, hence through their maximum peak responses before any destructive interference occurs. In between the notches, constructive interference takes place.

The simple resonent RLC circuit model is carried further to distributed transmission line models and external coupling to structures, the basis for most resonent system responses. The effects of the notches and the superposition are not changed appreciably by the distributed coupling of more realistic models.

Other nonsimple responses are also analyzed and discussed in the paper, but the main areas of concern are data evaluation, transfer function calculation, and extrapolation to nuclear criteria and environments. Methods are recommended for handling data evaluation and interpretation which, if not implemented and left to naive numerical methods, can result in gross errors.

-1-

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A 25 MHZ NOTCH IN THE HPD FACILITY OUTPUT: ITS SOURCE AND EFFECT

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The measured fields at HPD [1] show a notch in the spectrum at 25 MHz (figure 1). This notch is in addition to those observed due to ground reflections and pulser asynchronism. Its source can be found in derivative super reference sensor data (figure 2) which are free of ground reflection effects but not asynchronism effects. The super reference sensor data shows twin peaks separated by approximately 5 ns, followed approximately 20 ns later by a second pair of twin peaks also separated by approximately 5 ns. The first pair is the two pulser sides firing asynchronously by approximately 5 ns. The second pair, 20 ns later, is a "reflection" of the first two. They arise from diffraction/reflection off the bicone edge when there is an abrupt change in geometry and an impedance discontinuity. The "reflection" has an amplitude of ~0.4 of the original. Interference effects should therefore occur at a frequency with a period of twice that of the delay, or precisely at the 25 MHz observed. The notch should be of the order of 5 dB which is in good agreement with the approximately 6 dB observed. Finally, the delay of 20 ns corresponds closely to the transit time difference between radiation appearing from the bicone apex and that from the bicone edge.

This effect has long been suspected, but measurement difficulties and the wealth of data to be sifted through had precluded its earlier detection.

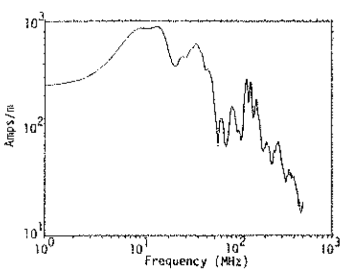

Figure 1. Nominal Frequency Domain Pulser Behavior

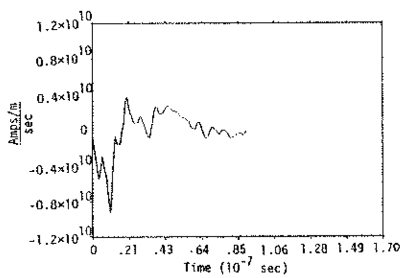

Figure 2. Nominal Time Domain Pulser Behavior

[1] Kunz, K. S., et al, "Horizontally Polarized Dipole Testing Program - Horizontally Polarized Dipole Characterization Report - Volume I, Part I - Field Analysis Report," AL-1265, EG&G, 31 August 1978

A TWO-PLATE TRANSMISSION LINE EMP SIMULATOR WITH IMPROVED CONTINUOUS WAVE (CW) PERFORMANCE

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The discovery of a deep notch in the magnetic field spectrum plus an associated standing wave interference pattern above about 20 MHz in the ALECS facility (1) and similar findings in the ARES facility (2) have lead to multiple approaches for mitigating the problem. Kunz (2) describes a technique implemented in ARES to scatter some of the unwanted energy out of the transmission line. Kunz and Giri (3) have described another technique which would, if implemented, absorb some of the higher mode energy in a resistive sheet or an array of discrete resistive elements.

A third approach has been evaluated experimentally on a small transmission line (approximately one-tenth the size of ALECS) and found to provide significant improvement in the CW performance of a two-plate line. This approach eliminates the parallel-line and output conic sections of the traditional simulator geometry and uses instead a large distributed resistive and inductive array to terminate the line. The array is very sparse so the majority of the high frequency energy radiates out of the array rather than being trapped within the array by multiple scattering. This greatly reduces the standing wave effects and eliminates the deep notch in the spectrum. The design has been implemented on two full scale EMP simulators in Europe.

This paper describes the scale model experiments performed and presents a comparison of the results with those observed in ALECS.

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(1) J.C. Giles, et al., "Evaluation and Improvement of the CW Performance of the ALECS Facility", ALECS Memo 10, September 1975.

(2) K.S. Kunz, et al., "Application of Reflection and Diffraction Techniques to the Analysis of an EMP Simulator", <u>IEEE Transactions on Antennas and Propagation</u>, <u>Vol. AP-27, No. 3</u>, May 1979.

(3) K.S. Kunz and D.V. Giri, "A Study of a Resistive Sheet Bifurcating an Infinitely Wide Two-Parallel Plate Line", NEM 1980, Anaheim CA, August 1980.

LINK, A 1 MJ, 1 MV, 20 Ω, 2 ms
HIGH ENERGY PULSE GENERATOR

by Donald F. Strachan
Physics International Company
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A 1 megavolt, 1 megajoule long pulse energy system, known as LINK, has been designed and is presently being constructed. LINK is designed to drive resistive loads ranging from short circuits to 1000 ohms. The system will deliver 2 coulombs at currents ranging from 1 to 50 kiloamps with an e-fold pulse duration of 2 milliseconds to 40 microseconds, respectively. LINK is easily reconfigured to generate 500 kilovolts, at 1 megajoule, delivering 4 coulombs at currents ranging from 0.5 to 25 kiloamps with an e-fold pulse duration of 8 milliseconds to 160 microseconds, respectively.

A description of the energy storage system, the gas transition region, and the dummy load configuration will be presented.

PULSER MODIFICATIONS AND WORKING VOLUME FIELDS IN THE ATLAS I (TRESTLE) FACILITY

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In attempting to determine the degree of hardening of aerospace systems to a nuclear ElectroMagnetic Pulse (EMP), it is often necessary to perform system level testing using a simulated environment. For such testing, it is important that the ElectroMagnetic (EM) field within the simulator be comparable to the EMP threat, in order to ensure reasonable confidence in the results of the testing. There are many complex factors which influence the production of the simulated EM field, including the physical and electrical design of the simulator and the pulsers which drive it.

Over the last few years, attention has been focused on the EM and parametric design of the pulsers in the ATLAS I (TRESTLE) facility. Some modifications in these pulsers have been studied both analytically (e.g. monocone switch impedance and orientation, peaking capacitor arrangement) and experimentally (e.g. pulse injection testing, peaking capacitance variation, transmission line improvement). In the performance of these experiments, additional sensors were installed in the pulser region and data taken with both electric and magnetic field sensors. In some cases, working volume fields were estimated from data taken in the pulser area.

This paper reviews and summarizes some of the results of the computational and experimental efforts outlined above.

"HEMP Analysis of a Buried Insulated Communications Antenna"

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The response of a buried insulated communications antenna to HAB EMP excitation has been computed. The antenna is buried parallel the the earth's surface at a depth of 1.25 m. It has a zig-zag geometry and a third harmonic resonant frequency at 450 kHz.

The analysis of the antenna utilized transmission line theory in the frequency domain with the tangential HEMP electric field as the distributed voltage source term[1]. The propagation constant, $k^{interface}$ and the characteristic impedance, Z_c were computed by an iterative procedure developed by Row[2,3] which solves the approximate boundary value problem formulated by Wait[4] of an insulated wire in the presence of a planar interface. The formulation is in terms of the average fields around the wire and requires that the burial depth be much greater than the diameter of the insulation. The propagation constant so computed is in good agreement with results generated by Head[5] who used an equivalent formulation.

The propagation constant will be shown as a function of frequency over the HEMP spectrum and compared with the propagation constant for an infinite ambient medium, k^{∞}. In addition, the current induced on an infinitely long buried insulated wire excited by a normal incident transient plane wave will be shown using $k^{interface}$ and k^{∞}. The comparison illustrates the effects of the interface on a nonresonant structure in the time domain. Finally, the results for the zig-zag antenna will be shown as a function of the angle of incidence and polarization of the incident HEMP. Mutual coupling among the antenna elements is ignored in all cases.

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IDENTIFICATION OF ANTENNA PARAMETERS FROM TIME DOMAIN PULSE RESPONSE DATA*

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An accurate antenna model is important to the determination of the responses of electronic systems to nuclear EMP. In our work, a transient electromagnetic antenna range provides pulse measurements from which antenna impedance can be obtained. One modeling technique previously used computes antenna impedance from time domain reflectometry (TDR) measurements using Fourier Transform operations. This paper describes a technique for obtaining a lumped parameter antenna impedance model directly from the time domain antenna range data. The method uses modern parameter identification techniques in which a pole-zero (autoregressive moving average or ARMA) model is obtained by recursively computing the model parameters which minimize time domain mean square error. The technique is described, and an example identification using actual antenna range measurements is given.

*This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore Laboratory under contract #W-7405-ENG-48.

SHIPBOARD ANTENNA SYSTEM EMP DESIGN ALGORITHM*

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A procedure for the design of shipboard antenna systems against the effects of electromagnetic pulse (EMP) is described. Exposure to EMP, especially that from a nuclear burst at high altitudes, can degrade the combat effectiveness of unhardened air-and-sea-based Navy communication systems. The design procedure, or EMP algorithm (EMPAL), is a computer-aided iterative process which relies on a blend of experimental and computational techniques. Scale modeling and a transient electromagnetic test facility (time domain range) are used to determine antenna system response functions. Lumped element models are used in combination with the circuit configuration and the EMP source as inputs to a circuit/systems simulation code (SPICE2) for response computations. The EMPAL procedure parallels the EMC (electromagnetic compatibility) design approach currently in use for Navy shipboard exterior RF communications sytems design. EMPAL will thus augment the Navy's EMC design capability.

*This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract #W-7405-ENG-48 and was sponsored by the Naval Ocean Systems Center under MIPR660181MP0009.

COMPARISON OF 1D AND 3D SREMP COUPLING MODELS†

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One of the most useful analytic tools for calculating SREMP coupling to long conductive lines is the 1D, time-domain, transmission line model. This model has been extended to include many site details for a typical system consisting of numerous buried, distributed conductors. Because of computer cost and time constraints associated with 3D codes, it is desirable to establish confidence in 1D models for treating such complex systems. The 1D model, however, has certain inherent uncertainties associated with calculating SREMP coupling to complex three dimensional systems with all the implied mutual coupling effects at work. To validate the ability of the 1D model to handle such site detail extensions, a test case is modeled using both 3D and 1D codes. The 1D transmission line analog of the test case is shown in Figure 1; numerous site details are included. Current and voltage comparisons between 1D and 3D are made for various selected observer locations. Current predictions on the power line system demonstrate excellent agreement between 3D and 1D. Also, early time (t $\leq$ 40 μsec) predictions on most site conductors for 1D exhibit good agreement with the 3D model.

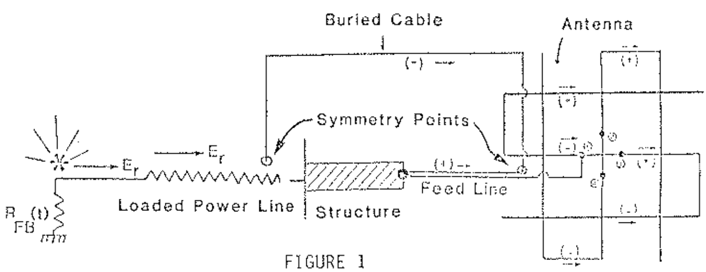

FIGURE 1

† This work was supported by the Boeing Aerospace Company under Purchase Contract No. C75651.

DEVELOPMENT OF AN IMPROVED HIGH ALTITUDE SOURCE REGION SIMULATION CODE

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To assess the impact of the X-ray deposition region EMP environment on aerospace systems, it is necessary to predict or estimate the magnitude and waveform of the induced electromagnetic transients within all interior cavities. A numerical model (computer program CIRCE[1]) of the X-ray deposition region is described in which the primary emission electrons are modeled by cloud-in-cell macroparticle techniques while secondary electron currents are modeled by a set of full fluid equations which include transport effects. Comparisons are made between model predictions and experimental data taken from literature and are shown to be in reasonable agreement. Recent enhancements to CIRCE will also be described along with their impact on the predictions.

A proper solution of the X-ray deposition region EMP problem requires the simultaneous solution of Maxwell's equations along with the equations of motion for primary emission and secondary ionization electrons. The primary and secondary electrons are accumulated to determine the current density J, which then drives Maxwell's equations. This results in a self consistent solution of Maxwell's equations and the electron trajectories.

The initial version of CIRCE made some simplifying assumptions on the equations of motion for the primary and secondary electrons. The assumptions being that the $\vec{V} \times \vec{B}$ term in the Lorentz force equation is negligible and that the gradient of the pressure in the fluid equations is negligible. The impact of these assumptions will be discussed along with the dependence of the solution on the type of differencing scheme employed. A costing algorithm will also be presented that will demonstrate that CIRCE is inexpensive compared to comparable SREMP codes.

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DEVELOPMENT OF A SYSTEM RESPONSE COMPUTER CODE

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In order to protect vital electronic equipment from upset or damage in a nuclear environment, systems are designed with features to mitigate EMP effects. Generally this involves one or more layers of EM shielding (i.e., Faraday cages) enclosing the electronics of each subsystem. However, these shields cannot be perfect. Their effectiveness is diminished because of leakage through apertures, diffusion through the shield, and IEMP. Another significant penetration is the interconnecting cables that enter each subsystem from outside its shield. This becomes especially important for large systems in which long cables are necessary. EMP signals on these cables are even present in a well designed system, one that uses shielded cables, plus another layer of protection by enclosing the cables in conduits. These signals are produced in two ways, by EM coupling and IEMP field generation. The EM coupling involves leakage through the shield by EMP fields that exist outside the shield, or by IEMP. EM leakage is by diffusion through imperfect-conductivity metal shields, or field coupling through holes, as in the many small interbraid openings in shielded cables. The IEMP signals result from gamma rays that can easily penetrate thin metallic shields and generate fields inside by ionization from scattering.

These effects have been studied before. Here we report on an effort to incorporate all the EMP cable driving effects together in a computer code. The aim of the project was to model the effects reasonably accurately without making the code too cumbersome. Specifically, it was designed to study real systems, with arbitrary physical configurations of subsystem enclosures and cables. The terminations at the cable ends were allowed to be nonlinear, since these may involve electronics or terminal protection devices. Flexibility was allowed in specifying the driving sources. The sources can be given explicitly, i.e., current functions on cable shields. However, simple models were also incorporated in the code for other drives, e.g., aperture and coupling models so the specified drive can be the fields outside the skin of the total system.

The code was designed for two uses. Because of its ease of use and fast running time, it can be used to easily analyze and compare various configurations and options for a system. Also, since it includes both EM coupling and IEMP, it can determine when it would be wasteful to spend more resources on improving shields because the EM coupled signal was already lower than the IEMP signal.

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under Contract Number DNA 001-81-C-0151.

Withdrawn

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INTERACTION BETWEEN AN ELECTROMAGNETIC PULSE AND A METAL CYLINDER CONNECTED TO A PARALLEL PLATE GUIDE BY A WIRE

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The interaction between an electromagnetic pulse (EMP) and a metallic cylinder, connected to one side of a parallel plate guide by a wire, is analyzed. The axes of the cylinder are collinear and perpendicular to the walls of the guide. The EMP is a transverse electromagnetic (TEM) wave with the electric field intensities of the frequency components being perpendicular to the guide walls. The surface currents and charges induced on the cylinder and wire surfaces are dependent upon the geometry or spatial dimensions of the structure normalized with respect to the width of the guide.

The combination of thick and thin cylinders, or thick cylinder and wire, is an analytical model or simulation of airplanes with refueling booms, trailing wire antennas, and ground-alert communications lines.

Two methods are presented for resolution of the field perturbations created by and the currents induced on these collinear cylinders. The first method is a two-dimensional solution of Laplace's equation by numerical approximation. This method is useful for solving many electromagnetic field problems which have geometrical shapes not amendable by rigorous mathematical techniques. It is a scheme of replacing differential equations by difference equations.

The second method introduces an analytical formulation to conformal mapping. It deforms a two-dimensional region into the upper half of the complex plane bounded by the real axis. The boundary of the region becomes the real axis. The expressions which map the boundaries of the region, usually a geometrical shape formed by straight line segments, provide formulations of the electric field and potential contours.

METHODOLOGY FOR MISSILE PLUME SIMULATION

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Under contract to DNA, Science Applications, Incorporated has developed a methodology for simulation of missile exhaust plume effects on EMP response. Simulation criteria and design concepts are briefly reviewed. The rationale for an active plume simulator is presented, together with design requirements for such a simulator based on preliminary simulation criteria.

EMP SIMULATION ON LONG CABLES

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EMP simulation on long cables using antennas is impossible due to the limited dimensions of the simulator.

In order to verify in such a case the validity of a previously developped numerical method of calculation of EMP response |1|, a procedure using impulse current injections in cable sheaths has been imagined. An impulse current was injected in the sheath of a coaxial cable of 450 m length and the voltage induced in the central conductor was measured using a transient digitizer protected by a shielded cage (fig. 1). The value of the induced voltage was also calculated using a similar computer model as the one of ref. |1|. This computer model is based on the theory of incremental sources |2|. The calculation is performed in the frequency domain using the Fourier transform of the impulse current injected in the cable sheath. The result is then obtained in the time domain by an inverse Fourier transform.

Comparison between calculated and measured date shows a good agreement (fig. 2). This comparison can be taken as a criteria for the validity of the mathematical model of the transfer between the sheath and the central conductor ot the cable. As the same model was used for calculating the cable response to an EMP it is possible to conclude that the model should give reasonable results also for long cables.

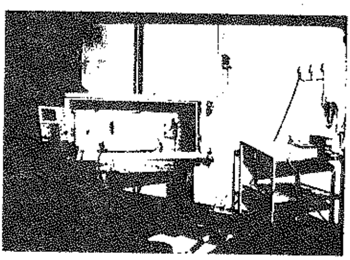

Fig. 1 View of the experimental layout

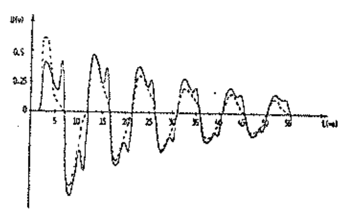

Fig. 2 Induced voltage vs. time
——— experimental data
– – – calculated data

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SIMULATION OF THE RESPONSE OF LONG CABLES IN THE AURORA TEST CELL WITH SLOW WAVE STRUCTURES

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Experience indicates that crucial elements of an extended system should be subjected to a time-varying air conductivity in order to obtain meaningful SREMP coupling data. As a simple example, let us consider a radio set attached to a relatively long horizontal antenna (for example, 50 m). The present limitations of the AURORA Mark I[1] source-region simulator volume make it impossible to subject both the radio set and the entire antenna to a simulated source-region environment. Another difficult source-region simulation task might involve the simulation of the response of a combined system consisting of an extremely long cable attached to an electronic system contained in an R.F. Shelter. The HDL SREMP Group has reported on techniques which can be used to design "shrunken" antennas which mimic the response of larger antennas. The underlying "shrinking" technique is to increase the density of the capacitive and inductive energy around the shrunken antenna in such a way that the air conductivity produced by ionizing radiation interacts with the shrunken version so that it mimics the system being modeled. The principal idea underlying the technique is that the effect of air conductivity is to produce a loss mechanism across the electric field surrounding the antenna. References 2 and 3 give empirical and calculated evidence indicating the usefulness of this basic concept. In this paper, we consider the possibility of modeling the response of very large systems such as long linear antennas and long cables with shrunken slow-wave structure versions that are at least an order of magnitude smaller that the systems being modeled.

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*This work was sponsored by the Army and DNA under Subtask X990AXVD/EMP Vulnerability Hardening and Testing and Subtask X99QAXVC/CMP Environments and Coupling.

RECENT DEVELOPMENTS IN SOURCE-REGION EMP SIMULATION

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The AURORA, the free world's largest flash x-ray machine, was originally designed to simulate strategic transient radiation effects on electronics. During the last five years, Harry Diamond Laboratories (HDL) has devised methods that allow the AURORA to be used as a tactical and a strategic source-region electromagnetic pulse (SREMP) simulation tool.[1-5] In an actual tactical SREMP, the electromagnetic field is produced by Compton current drivers that extend over large volumes. Any attempt to use the Compton electrons produced by the AURORA to serve as the source current to generate a tactical EMP simulation is inadequate because the AURORA test cell and the spatial distribution of Compton electrons produced by the AURORA are much too small.[1,2] To achieve the proper balance of ionizing radiation plus electromagnetic field necessary to simulate the tactical SREMP, a large transmission line was constructed in the AURORA test cell so that the line could superimpose an electromagnetic field on the AURORA-produced ionizing radiation.[1,2] In the deep strategic source region, the air conductivity can be as high as 0.1 mho/m, the skin depth is small, and the local electromagnetic field is produced by Compton electron drivers extending over a relatively small volume of space, that is, a volume less than a few cubic meters. For the strategic SREMP, "local effects dominate," and a credible simulation has been achieved by direct electron injection.[3,4] The technical problems and the theoretical justification for the use of the AURORA as a SREMP simulation tool will be presented. Techniques for analyzing the response of Army systems to a SREMP environment also will be discussed.

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MICROWAVE, BIASED MICROWAVE, D.C. PIE PAN,
AND RESONANT CAVITY AIR CONDUCTIVITY MEASUREMENTS

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This talk discusses four related topics--(1) microwave conductivity measurements, (2) microwave conductivity measurements in a waveguide with a superimposed dc field, (3) dc pie pan ionized gas conductivity measurements[2], and (4) ac resonant cavity measurements of ionic conductivity.

When the AURORA is used in SREMP-related experiments or tests, a great deal of ionizing energy goes to waste. The Harry Diamond Laboratories (HDL) SREMP group has designed a number of relatively inexpensive unobtrusive "piggy back" conductivity measurements which can be used to yield air chemistry data of central interest to the EMP community. Recent low pressure air conductivity experiments using L-band microwave techniques will be discussed.

The basic goal of the work is to understand both the microscopic and macroscopic properties of ionized air and also to examine whether other gases might be substituted for air in order to obtain a more cost effective source-region simulator.

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A DISCUS SREMP SIMULATOR FOR LONG BURIED OBJECTS*

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A ground based installation hardened to a Source Region Electromagnetic Pulse (SREMP) environment can be partly decoupled from SREMP coupling uncertainties by burying all conductors. The SREMP interaction problem can then be separated approximately into two parts: determining the electric and magnetic fields at the surface of the earth due to Compton interaction in the air and conduction in the air and earth, and establishing the coupling of the electric and magnetic fields in the earth into critical equipment. A particular version of the DISCUS** (Ref. 1) simulation concept has been studied to produce threat level fields into the earth near long narrow objects, such as buried antenna wires and horizontal missile shelters. The system consists of a row of small early-time pulsers, whose triggering is phased to simulate the sweep of the SREMP waveform across the earth, and a large late-time pulser coupled to the earth via an array of overhead wires similar to a shorted SIEGE array. This paper presents an overview of the design considerations for pulsers and earth contacts, including candidate test configurations.

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* This work was sponsored by the Air Force Weapons Laboratory under contract F29601-79-C-0043.

** Distributed Source Conducting Medium Underground System Simulator.

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CALCULATION OF THE EARLY-TIME PERFORMANCE OF A DISCUS SREMP SIMULATOR*

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The problem of system hardening has focused attention on the need to test the EMP response of buried conductors to EM fields produced in the source region. The design of a simulator to perform such a test poses many technical challenges because of the time scales and amounts of energy involved, and because of the possibility that a large object such as a buried shelter or wire would significantly alter the fields produced by the simulator. Presented herein is a theoretical study of the DISCUS simulator design (Ref.1) for early-times (up to 500 ns) for the purpose of demonstrating the validity of this design as a source-region EMP simulator. In addition, attention has been given to various structural aspects of design for the putpose of optimizing simulator performance under different test conditions.

The basic early-time DISCUS pulser design involves a connected series of single DISCUS pulser modules. The configuration that has been considered consists of 51 plates, each 1 meter high, 10 meters wide and .25 meters thick, with .75 meter spacing between the plates and the plates connected at the center by a high voltage pulser. Since the DISCUS array may be used together with an even larger array which would serve as a late time driver, the end plates here were assumed to be infinitely large. The pulsers are fired in sequence to simulate the sweep of a radiation pulse across the region. Each pulser is assumed to produce a similar waveform representative of the radial electric field in the source region.

Using the AUR3D code we have been able to model the DISCUS array and consider the effects of various soil parameters as well as the effect of different designs of the DISCUS simulator itself. Comparisons have been made to an actual source-region EMP environment with good correlation--given the uncertainty in possible SREMP environments the system might be exposed to, the differences in response observed would seem to be insignificant.

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A DISCUS SREMP SIMULATOR IN LATE-TIMES*

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A theoretical study is made of the DISCUS SREMP simulator design consisting of an array of single DISCUS pulser modules together with a late-time pulser designed to extend the threat environment to the time scale of several microseconds. The early-time pulser system is discussed in a separate paper (Ref. 1); the proposed late-time pulser design is a voltage source applied across one end plate of the early-time pulser system at ground level vertically to a horizontal mesh of wires raised two meters off the ground which is, in turn, connected to the other end plate. This design is similar to a shorted SIEGE array. The fact that this array is not terminated in its characteristic impedance has a beneficial effect upon design. The loss of current output due to the impedance matching would significantly reduce the output of the late-time pulser while the reflections of high frequencies at the termination are not significant since these frequencies do not propagate in this design. (The early-time DISCUS design provides the high frequency driver).

A numerical study of this system was performed using the three-dimensional cartesian Maxwell solver, AUR3D. A major technical problem of the validity of the deep-buried boundary in late-times was overcome by applying a solution to the diffusion equation at that boundary. A comparison with reference studies show this method to be a powerful technique. The study of the DISCUS SREMP simulator demonstrated the viability of the combined excitation concept. The calculation, which used a simple series RLC equivalent circuit representation of the early-time pulsers, revealed an undesirable interaction between the two pulser systems. The sum of the early-time pulser voltages exceeded the late-time pulser voltage at its turn on, driving current backwards through the overhead conductors. Subsequent slow oscillations were produced by the large inductance of the air space when current reversal followed discharge of the early-time pusler. Combined operation appears to require an early-time pulser whose voltage rises rapidly to the required peak value and then falls rapidly to a lower steady value. Apart from this feature, comparisons to a realistic SREMP environment showed good agreement.

* This work was sponsored by the Air Force Weapons Laboratory under contract F29601-79-C-0043.

** Now at Jaycor, P.O. Box 85154, San Diego, CA 92138

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EMP COUPLING TO CANONICAL MISSILE MODELS CONSISTING OF DIELECTRIC AND METAL SECTIONS

BY

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ABSTRACT

This paper presents the results of a finite difference analysis of EMP coupling to simple cononical missile models consisting of sections of metal representing the nose cone and nozzle ring, and a dielectric section representing a fuel bottle. An interconnecting raceway cable is included in the analysis to provide direct coupling between the metal sections in the missile model. Calculations from parametric variation of the dielectric properties of the fuel were performed in order to evaluate the nature and magnitude of the effects of the dielectric on total model response. Both conductive and non-conductive dielectric sections were considered here. In addition, variations in the raceway cable position and diameter were performed to evaluate the effects of the dielectric response on the cable.

Perhaps the most interesting and important results from the canonical analysis of missiles is the prediction of a dielectric cavity resonance within the missile fuel bottle. This resonance strongly affected interior response data and was also coupled to the wire and metal sections of the model. As should be expected, both the response amplitude and frequency of the dielectric mode were found to depend on the relative dielectric constant of the dielectric media (ε_r). The principal frequency of the response was found to satisfy the cavity mode relationship.

$$f = \frac{c}{d}\sqrt{\frac{1}{2\varepsilon_r}} \quad , \quad c = \text{velocity of light; } d = \text{width of cavity}$$

Another expected result of this analysis indicated that a certain amount of shielding of the interior regions of the model can be expected when the dielectric region is made conductive. The more conductive the region, the more nearly the response current will be restricted to the outside of the region due to the skin depth phenomena. This result has direct applications in understanding coupling to a conductive plume and also for interpreting conductive missile fuel responses.

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EMP RESPONSE OF COMPLEX MISSILE STRUCTURES

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Modern strategic missiles use dielectric fuel tanks as structural members. The response of such missiles to EMP can be quite different from that of the traditional metal enclosed tank that responds as a fat dipole. The new missiles generally have a metal raceway connecting conducting interstage rings and, as a result, have often been modeled as a dipole with alternating cylinders of large and small radii. However, previous analyses using the THREDH finite difference code have produced responses that differ from the dipole response.

To increase confidence in the THREDH calculation, a series of simple models were analyzed, the models ranging from metal and dielectrics cylinders to others with alternating metal and dielectric sections. Runs were made with and without raceways. External currents on metal cylinders peak in the center, while the current on a dielectric cylinder is uniform along the cylinder. When metal and dielectric sections are intermixed, and with raceways, the total current including the raceway current tends to be uniform along the cylinder, unless the raceway is very large. Accurate modeling of the raceway appears to be very important. The relative lengths of the metal and dielectric sections have an effect on the ratio of raceway and displacement currents.

Effects of a simulated plume in an EMP simulator were also studied. The electrical properties of plumes and their attachment to missiles have not been completely determined and very little work has been done with complex metal and dielectric missiles. The results of this study provide some insight into these effects.

EMP COUPLING TO A COMPOSITE CYLINDRICAL SHELL

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A three dimensional model of a closed finite semiconducting cylindrical shell (canister) was developed using resistively loaded wire segments to reflect the electrical properties of the composite material. The response was determined using a frequency domain method of moments code. Using engineering estimates of the resonant frequencies, the frequency sampling was limited to those in the vicinity of the estimated resonances. These results were used to determine the coefficients of a series of damped sine wave responses for the time domain impulse response. This series was then convolved with a double exponential forcing function to estimate the true time domain response.

Results were compared with one and two dimensional transmission line models. Agreement was generally good which indicates: compatibility of the separate modeling approaches; and probable validity of the results.

ANALYTICAL SOLUTION FOR EMP COUPLING TO MISSILE EXHAUST PLUMES

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Conventional solutions to the problem of EMP coupling to missile exhaust plumes treat the missile and plume as a dipole antenna with a series of discrete loads. These formulations suffer from a limitation in the number of discrete loads which can be included in the model because of matrix inversion problems.

A new formulation of the problem has been developed which allows the impedance of the plume to vary continuously. The current on a dipole with impedance per unit length $\eta(z)$ can be shown to satisfy the integral equation.

$$I(z) = I_s(z) - \int_{-h}^{h} I(z') \; \eta(z') \; I_V(z,z') \; dz'$$

where 2h = length of the dipole,

I_s = current which would be induced on an unloaded dipole,

$I_V(z'z')$ = current on a dipole at point z due to a unit voltage driver at z'

Techniques for solving this integral equation will be discussed and numerical examples will be given.

COUPLING TO VARIOUS AIRCRAFT CONFIGURATIONS

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An extensive analytical EMP coupling study has been performed for an aircraft in three basic modes: in-flight, ground alert, and refueling. In order to study the influence of several key parameters of the HAB coupling to the aircraft, several configurations were carefully selected. The parameters considered were wing position, wing loading (fuel tanks), refueling by a tanker, aircraft tie down and finally perfect verses imperfect ground planes. These configurations were chosen such that the influence of each parameter could easily be isolated and studied.

Of particular interest were the imperfect ground configurations and the significant differences in aircraft response (at EMP frequencies) when comparing the more exact Sommerfeld formulation [1] to the popular but approximate Reflection Coefficient method. Also compared were the use of the thin wire versus the extended thin wire kernels. Numerical results for the skin response under the various configurations have been computed and compared with the available full scale test data. Several key observations were made to assist future worst-case aircraft configuration selection.

[1] J. N. Brittingham, E. K. Miller, and J. T. Okada, "Bivariate Interpolation approach for efficiently and accurately modelling antennas near a half-space," Electronic Letter, Vol. 13, PP. 690-691, Nov. 1977.

ANALYTICAL AND EXPERIMENTAL VERIFICATION OF EMP EFFECTS ON CONDUCTIVE ROCKET MOTOR PLUMES, NOZZLES AND IGNITORS

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The paper describes the analytical and experimental effort conducted on small rocket motors to verify the EMP effects on a conductive plume and subsequent coupling of energy to the rocket motor nozzle and the ignitor (located at the forward end of the motor).

During the analytical portion of the program, motor chamber, nozzle and plume chemistry codes were exercised to determine the electron densities and collision frequencies present in the motor-plume system. The outputs of these codes were then used to input plume coupling codes which determined electromagnetic coupling to the plume, nozzle and ignitors. The motors analyzed were small (3 inches in diameter and 30 inches long), had electro-grade carbon nozzles and end plugs, and fiberglass cases. The propellants were similar to those used in MX motors.

The experimental portion of the program involved mounting the motors vertically (nozzle up) in a dielectric stand above a wire mesh ground plane. The motor-plume systems were then driven a monopole antenna over a ground plane. Two types of excitation techniques were employed. First, the motors were driven as base-driven monopoles and second, a monopole antenna was set up in the vicinity of the motors and the scattered field was used to excite the system. The current at the base of the motor-plume "antenna" was measured to examine the effect of the coupled current or field onto the plume, nozzle and end-plug (ignitor).

The driver for the measurements consisted of a spectrum analyzer, tracking generator, power amplifier and antenna transition network. A balanced current probe was used for the base current measurements which was then routed to a balun and subsequently to the input of the spectrum analyzer. In this manner the entire frequency spectrum of interest (1-100 MHz) was examined by sweeping the tracking generator through the frequency range several times during each motor burn.

Analytical and experimental results confirm the coupling of energy, both to the nozzle and down the motor chamber to the ignitor, when driven directly. Experimental results also confirm the coupling of energy onto the plume and to the motor nozzle from a scattered EM field. The effect was greater than predicted by the plume codes, and a study is currently underway to determine the source of the discrepancy.

This work is sponsored by Headquarters, Defense Nuclear Agency.

CIRCUMFERENTIAL CURRENT DISTRIBUTION OF AN AIRCRAFT ON THE GROUND

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The present method [1] used to compute the circumferential variation of the axial current density of an aircraft is to add the first order term ($2\underset{\sim}{n} \times \underset{\sim}{H}$) of the current density induced on an infinite cylinder in free space to the axial current density computed by a method-of-moments code such as NEC [2]. This correction to the current density is used in the external coupling analysis of an aircraft in the airborne mode and has been shown to improve the airborne results in comparisons with scale model data. The same correction to the current density is used for an aircraft in the ground alert mode, but the results do not improve this computation as significantly as in the airborne case.

In this paper we determine the circumferential correction to the current density for an aircraft in the ground mode by considering the distribution of current on an infinite cylinder over a ground plane. The effects of higher order terms in the expansion of the current density for an infinite cylinder in free space and over a ground plane are examined and the results are compared to scale model measurements to determine the significance of these terms in the aircraft coupling analysis. The current density induced on a finite cylinder in free space is examined and the results are compared with those of the infinite cylinder.

[1] C. D. Taylor, "External Interaction of the Nuclear EMP with Aircraft and Missiles", IEEE Trans. Antennas and Prop., 64 (1978)

[2] G. J. Burke, and A. J. Poggio, "NEC Program Description, Part I: Theory, Part II: Code, Part III: Users guide,", Air Force Weapons Lab. Tech. Rep. AFWL-TR-76-320, Sept. 1976.

INFLUENCE OF IMPULSIVE ELECTROMAGNETIC FIELDS
(EMP) ON ELECTRONIC SYSTEMS:
DURING STORAGE IN DEPOTS AND MISSION IN SEA-WATER

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Theoretical investigations are reported concerning the disturbance of military electronics by impulsive electromagnetic fields - caused by e.g. lightning, strong radar beams, and nuclear EMP. The electronic weapon systems are considered during EMP-influence under various conditions: the weapon system being stored in the ordnance depot, installed at the weapon platform (ship or submarine) ready for action, and finally the weapon during its mission - e.g. underwater vehicle marching in sea-water coupled with electric cables to the ship.

The consequence of impulsive electromagnetic fields, acting on weapon systems, is difficult to predict and strongly dependent on the sensivity and structure of the electronics in the weapon. However, the interfering influence of EMP can be predicted by theoretical computations dependent on the kind of the nuclear weapon (High-Altitude-EMP or Low-Altitude-EMP) as well as on the situation of the electronic weapon systems (e.g. during storage in depots and during mission in sea-water).

By theoretical computations the following questions are tried to be answered systematically: which electric and magnetic field strength disturbs electronic systems stored in more or less EMP-shieled rooms, or installed on ships or submarines; which time dependence show the influenced EMP-signals, and which voltage signals in secondary loops - caused by EMP - are to be expected; which electric and magnetic field strength is expected in sea-water with different proportions of salt and with increasing water depth; Which current signals are to be expected in electric cables in sea-water (two-wire lines, control lines of e.g. underwater vehicle)?

An extensive compilation of theoretically investigated results is given concerning weapon systems influenced by EMP during storage in depots and during their mission, especially in sea-water. Possible applications of the general results to special weapon systems are discussed.

Reference:

C.E. Baum,	EMP Interaction, Principles, Techniques
J.P. Castillo,	and Reference Data
J.H. Darrah,	Air Force Weapons Laboratory (NTMT),
	Kirtland Air Force Base, New Mexico, USA,
	Dec. 1980

EMP COUPLING TO A PARTIALLY SHIELDED CABLE

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A method of computing the load currents for a partially shielded cable illuminated by plane waves is presented. This analysis is accomplished by considering a superposition of the coupling due to the shielded portion of the cable, the exposed portion of the cable, and the pigtail termination of the cable shield. Standard transmission line theory is employed to compute the load currents for the exposed and shielded portions of the cable. The exposed portion of the cable is modeled as a single line over a ground plane. The shielded portion of the cable is modeled as a single line covered by an imperfect shield over a ground plane. An inductive coupling mechanism is used to compute the contribution to the load currents from the pigtail termination of the cable shield. Numerical results are presented and degradation of shielding effectiveness is discussed.

THEORY OF PERFORMANCE AND COST-TO-HARDEN OF LARGE C^3I NETWORKS UNDER NUCLEAR-STRESSED AND ECM CONDITIONS*

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A theory for predicting the performance and survivability of large redundant path C^3I networks under nuclear-stressed and ECM conditions is developed. These communication systems (typified by the PACOM networks) possess nearly a thousand nodes (message centers, relay terminals) and propagation links ranging from VLF to SHF. The networks include numerous critical message centers (e.g., command posts), with the required performance between them generally being different. The performance of a network is evaluated in terms of a set of functions $F_\mu(z,t)$ which for the μ^{th} command post pair is defined as the probability that the character error rate (CER) is less than or equal to z, at time t following the onset of the threat. It is shown that $F_\mu(z,t)$ is of the form:

$$F_\mu(z,t) = \sum_\ell G_\ell(z,t)\overline{P}_\ell(t) + \sum_m \sum_n G_n(z,t)\, G_m(z,t)\overline{P}_n(t)\overline{P}_m(t) + \sum_q \sum_r \sum_s \ldots$$

where the $\overline{P}$'s are functions of the products of the individual probabilities of survival, P_i, for the nodes, and the G's are functions of the link parameters. The $\overline{P}$ and G functions depend upon the entire connectivity between the command post pair and hence incorporate a part of the redundancy in the system. Whereas the nodes are modelled as binary random variables, the links have a continuous distribution in CER due to degradation of the propagation medium caused by nuclear detonations. Numerical methods for computing $F_\mu(z,t)$ are presented.

Using the aforementioned equation for F_μ we find the minimum cost to achieve network survivability by first selecting the required CERs between command post pairs, z_μ, and the time t_o at which minimum performance is to be achieved. We subsequently express the network cost function as: $C_{NT}=\Sigma C_i(P_i)$, where $C_i(P_i)$ is the cost required to harden node i to probability of survival P_i, and N is the number of nodes. Minimizing C_{NT} subject to the set of inequality constraints, $F_\mu(z_\mu,t_o) \geq H_\mu$ = constant = required time availability for each μ gives the minimum cost for network survivability. The relevant mathematical algorithm is discussed. Several realistic examples of the performance evaluation and cost-to-harden are rendered.

* Work performed under contract DNA-001-79-C-0162

DETERMINING PROBABILITY-OF-SURVIVAL OF COMMUNICATION-FLOW THROUGH LARGE NETWORKS SIMULTANEOUSLY STRESSED BY EMP AND MHD

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Analytical studies of the ranges of coupling and failure levels are used to define a probability of interrupt for critical communication elements.

Failures can occur at a multiplicity of locations, and at different times, in the network. This is due to the combined effects of; different time histories of EMP and MHD, the response times associated with the individual failure mechanisms, and propagation of the faults within the network. Some upset modes create outage times equivalent to that of equipment damage.

The probability of interrupting communications flow and the probable durations of such interruptions depend on well known interdependent reactions within the communication network and the specific nodal interconnectivity involved. Probability-of-Survival is developed in terms of Percent-Time-Availability, during scenario for call initiation and message transmission.

Results of the modelling of coupling and failure modes and nodal interconnectivity are given. Methods for optimizing network designs to promote lowest cost with highest survivability are discussed. The effectiveness of linear hardening techniques and the benefits to hardness maintenance are also discussed.

EMP-HARDENING OF EXISTING C^3
GROUND FACILITIES

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Alternative techniques are described for the low-cost but effective EMP-hardening of existing critical command, control and communications (C^3) facilities.

The approaches outlined will utilize low-cost add-on shielding techniques, combined with effective penetration protection for high confidence in the survivability, and minimum life-cycle costs. Corrosion control techniques and EMP hardness monitor systems assure that survivability is maintained for a twenty-year life, again at low cost.

New techniques are employed for obtaining the required shielding-effectiveness. Shields are applied to the exterior of some facilities, and to the interior of others. New filters, or fibre optics, are employed for telephone circuits. Special attention is given to penetration panels and grounding.

Implementation techniques are designed for essentially no shutdown during installation. Thus, there is no interruption of operational service, or disruption of normal operations of personnel.

Costs are low in relation to the facility costs and very much less than the cost of new construction.

Work performed under the auspices of the Defense Nuclear Agency (Contract No. DNA001-80-C-0257) and the Air Force Weapons Laboratory (Contract No. F29601-80-C-0036) (Subcontract SC-0036-80-003).

ELECTROMAGNETIC SHIELDING PROVIDED BY WALLS.
APPLICATION TO BUILDINGS WITH TELECOMMUNICATION EQUIPMENT

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For the electromagnetic waves, walls of buildings can be considered, in a first approximation as the superposition of a low conducting material (brick, concrete) and a wire mesh screen. To determine theoretically the shielding effectiveness of these walls, the simplest solution is to study successively the penetration of a plane wave on a conducting layer and on a wire mesh assumed to be infinite in extent. In this paper we compare the theoretical and experimental values of the shielding in time domain and also as a function of frequency in the 1 MHz - 500 MHz range.

At first, measurements in time domain have been made inside an E.M.P. simulator. A metallic box with an open side has been used. This side, with a surface of about $1 m^2$, can be filled with a concrete wall, a wire mesh, a metallic plane in which various holes have been made... A comparison of the shielding effectiveness of these various structures is given.

Then the inherent shielding provided by building structures, where telephone exchanges are set up, were measured in frequency domain. As a source, A.M. and F.M. broadcast transmitters can be used. However in order to avoid field amplitude fluctuations and to fill the various gaps in the frequency range, mobile transmitters were used with a rhombic antenna in the 3-30 MHz range and Yagi antennas between 50 and 500 MHz. The H.F. radiated power was about 50 Watts, the transmitter being situated at few hundred meters of the double story buildings under test. The external field were measured at various points: on the roof, at the first and at the ground level. Interior measurements have been made at various distances from the outer walls and near the electronic equipments. A comparison of the electric-field and magnetic-field attenuation is given.

THE EMP SHIELDING PROVIDED BY PRE-ENGINEERED METALLIC BUILDINGS

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Pre-engineered metallic structures (e.g., Butler buildings) are often suggested as a means to provide EMP shielding for C^3 assets. These structures are relatively inexpensive and can be quickly constructed. The question naturally arises regarding how much shielding they really provide. The objective of the work summarized in this paper is to evaluate this shielding.

The approach is experimental. A Butler hut (20'W x 25'L x 12'H) was constructed according to standard specifications at Harry Diamond Laboratories' Generic Verification Facility (GVF) at Woodbridge, VA. It was positioned such that it could be illumined by either a vertically or horizontally polarized transient source. Responses (energy dissipated in load resistors) of a large loop and dipole were measured inside the structure for three orthogonal orientations at a large number of locations. These were compared to the responses measured at the same locations before the structure was in place. The configuration of the structure was varied: the entrance door was either open or closed, and the metal building was either floating or connected to the earth ground system by welding #6 steel wire between the GVF rebar mesh and the structure panels at two foot intervals along all four walls.

With the door closed, the shielding was measured to be between approximately 4 and 30 dB, with most results in the 10 - 20 dB range. With the door open, the shielding decreased markedly, and in fact, enhancements (negative shielding) were noticed. Connections of the structure to the earth ground system resulted in 2 - 8 dB changes. In most cases the shielding was increased by making this earth ground connection, but it was reduced in other cases.

DEVELOPMENT OF CRITERIA FOR PROTECTION OF HIGH EFFICIENCY VLF AMPLIFIERS*

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The Very Low Frequency (VLF) transmitting stations are key to Navy strategic communications with submarines. The existing VLF transmitting systems are in the process of being replaced with technologically new high efficiency, high power (megawatt) amplifiers which are potentially vulnerable to the threat from the high altitude nuclear electromagnetic pulse (HEMP). Preliminary hardening criteria or guidelines have been established through consideration of some of the general aspects of all the fixed VLF sites, analysis of a specific site antenna configuration, and prior work on other communication facilities. The criteria presented are to provide a basis for future development work for the amplifier systems under consideration.

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PROTECTION AGAINST LIGHTNING AND EMP SURGE VOLTAGES BY MEANS OF GAS ARRESTERS AND SPECIAL DIODES

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Impulsive electromagnetic interferences are able to cause extreme surge voltages on cables. Dependent on risetime and magnitude these surge voltages may disturb and under certain circumstances destroy electronic systems. In principle it is possible to suppress these transient voltages by means of special protection circuits.

In the following the most unfavourable case concerning voltages limitation is assumed, that is an unsymmetrical cable and therefore a coaxial construction of the protection circuit. These circuits are available for lightning surges with edge steepnesses of about 2 kV/µs. The output voltages of these circuits are limited to e.g. 24V. In case of NEMP there exist much higher edge steepnesses up to a value of 10 kV/ns, therefore the limitation of the output voltage to values less than 100 V is more problematic than in case of lightning.

The behaviour of different gas arresters is investigated experimentally for transient voltages with edge steepnesses up to 10 kV/ns. In connection with very quick diodes with response times less than a few pico-seconds (theoretical) and a large peak power dissipation it is possible to realize a passive protection circuit against extreme surge voltages. The protection circuit developed has a coaxial construction with the following features: 1. 50Ω-technique; 2. maximal output voltage equal to or less than 100 V for surge voltages with edge steepnesses up to 10 kV/ns (NEMP) in consideration of a minimum insertion loss.

SURGE ARRESTERS AS EMP PROTECTIVE DEVICES

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Specifications for transients in the nanosecond time regime are usually not given for commersially available surge arresters. Hence, there is a great uncertainty if such arresters are fast enough to protect against EMP surges with rise times considerably shorter than 100 ns.

An experimental investigation has been undertaken of several surge arresters. The experimental results have been interpreted using a simple theoretical model. Pulses with a 4 kV/ns rate of rise were used during the experiment. It was found that all the arresters consisting of an air spark gap in series with a varistor have a sufficiently fast response for EMP protection purposes. To obtain this fast response requires that the connector leads are short to make the inductance low. The experiments also show that there is little to gain in changing the design of the spark gap and internal leads, the reason being that the main part of the inductance is often due to external connections. For comparison purposes the arresters was replaced by a copper piece shaped as the arrester itself, and no appreciable enhancement of the protecting efficiency was observed. It is, however, quite possible to achieve an integrated design of the arrester, connectors and a low pass filter into a combined unit which provides an appropriate degree of EMP protection.

ABSTRACT

AVSHELL--AN IMPROVED BACKSHELL DESIGN*

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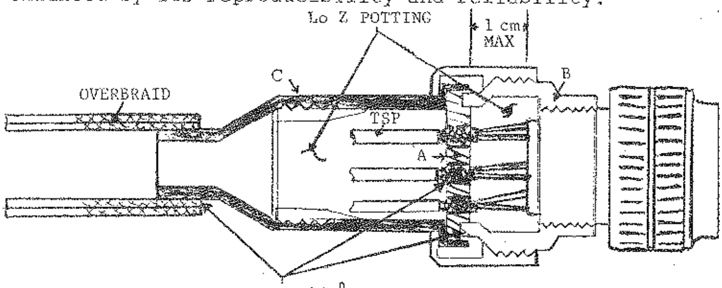
The AVSHELL backshell provides complete peripheral bonding of all cable and wire shields to the backshell and backshell support. It does so with minimal disturbance to the inner-wire emission suppression compound, thus meeting zero-length termination constraints, important for SGEMP control. Significant electromagnetic and SGEMP hardening benefits result so that the cable assemblies perform up to their maximum theoretical capabilities, limited only by the braid shields. The transfer impedance of the cable assembly at 100MHz is far below the assembly DC resistance.

The figure below outlines the salient features of the design. At the heart of the concept is the peripheral tinned bonding of the twisted wire pair (TSP) shield to the terminating disk (A) and the disk to the backshell support (B) and backshell(C). This termination eliminates all pigtail coupling effects within the backshell and connector. The cable overbraid is tinned to the backshell, and the entire backshell is filled with low-Z potting, further controlling SGEMP response of the backshell and connector. The tinning is done by a vapor phase reflow process that heats the backshell components and shields quickly and uniformly. The design is further enhanced by its reproducibility and reliability.



TIN FLOW AT ALL MECHANICAL JOINTS

*This work was supported by the U.S. Air Force under contract F04704-79-C-0062. Patent Pending.

ELECTRICAL BREAKDOWN CHARACTERISTICS OF SOIL

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When a large voltage pulse is applied between two conductors that are buried in soil, the soil will break down electrically and a large current will flow between the conductors. The breakdown process in soil is characterized by a threshold field for breakdown, a delay time between application of the voltage pulse and the breakdown, and the postbreakdown I-V characteristics.

The threshold electric field for breakdown is a function of the soil water content (probably because of its effect on the soil electrical-conductivity and dielectric constant) and soil type (probably because of grain size). For very long pulses and water contents around 7% by weight, threshold fields are on the order of 1 MV/m. For drier samples, the thresholds increase to about 2 MV/m.

The delay time before breakdown is primarily a function of how far the voltage pulse is above the threshold. Close to the threshold, the delay time can be very large ($\gtrsim$ 1 ms) but it decreases rapidly to 10 to 20 μs at fields of 2 to 3 MV/m and less than 1 μs at fields of 8 to 10 MV/m, for meter-size distances between the electrodes.

When the breakdown occurs, the voltage across the sample decreases rapidly while the current increases. The maximum current that flows during a breakdown is limited almost entirely by the pulser characteristics (its initial voltage, capacitance, inductance, and series resistance). The breakdowns occur as discrete, high-current paths (streamers) through the soil. However, a previous breakdown channel does not appear to be a preferred path for a subsequent breakdown. The minimum impedance that an arc attains during a discharge decreases with the amount of current that the pulser can drive through it. For meter-size arc lengths, the minimum arc impedance is on the order of 2.5 Ω/m for a peak current of 5 kA and 0.25 Ω/m for a peak current of 50 kA. At the time of the minimum arc impedance, the arc current is less than the peak value, and the electric field along the arc is on the order of 1 to 10 kV/m.

Arcs prefer to travel below the surface of the soil rather than along the soil/air interface. Arcs which were initiated by a 5-cm-radius electrode at the soil/air interface immediately dove below the surface, if there was no debris on the surface, and remained underground until they reached the second electrode, which was a vertical conducting plane that intersected the soil surface. However, when a small green twig was placed on the surface of the soil a slight distance from the 5-cm electrode, the arc jumped to the twig, followed it for a few centimeters, then disappeared below ground, then returned to the twig, and finally disappeared below ground for the last 30 cm from the end of the twig to the planar electrode.

EARTH BREAKDOWN IN CYLINDRICAL GEOMETRY*
I. IMPEDANCE CHARACTERISTICS

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Electric breakdown of earth around buried conductors is an important facet of nuclear EMP coupling to long lines. Earth samples with coaxial cylindrical electrodes were subjected to multi-millisecond long high-voltage pulses. The effective resistivity of the earth as a function of electric field and time after application of the field was determined by measuring the radial voltage profile with high-impedance voltage probes. The results for 300 Ω m samples are:

1. The threshold electric field for streamer initiation was 1000 kV/m for .002 m^2 electrode area.
2. The threshold electric field decreased with increasing electrode area.
3. Streamers propagated outward in diverging electric fields down to ~100 kV/m.
4. The streamer resistance decreased with time to ~300 μs.
5. The streamer resistance decreased with increasing current. Electric fields lower than 10 kV/m were measured at ~100 A.
6. The earth resistance recovered with decrease in current within <500 μs.

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*This work was sponsored by the Air Force Weapons Laboratory under contract F29601-78-C-0082.

EARTH BREAKDOWN IN CYLINDRICAL GEOMETRY*
II. DEPENDENCE ON SOIL TYPE

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Soils with resistivity between 100 and 7000 Ohm-m were subjected to high voltage pulses of multi-millisecond duration in coaxial cylindrical segment geometry. The earth resistivity as a function of electric field and time after application of the field was determined by measuring the radial voltage profile with high-impedance voltage probes. The results include:

1. The threshold electric field for streamers initiation increased by a factor of 2.5 for resistivities increasing from 100 Ohm-m to 7000 Ohm-m.
2. The apparent relaxation time at which the streamer resistance comes to equilibrium at a given current is ~50 μs in 7000 Ohm-m sand, ~100 μs in 1000 Ohm-m sand, and ~300 μs in 300 Ohm-m sand.
3. The streamer resistance at high currents appears to be almost independent of initial soil resitivity.

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EARTH BREAKDOWN IN CYLINDRICAL GEOMETRY*
III. STREAMER STRUCTURE

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The streamer structure produced in coaxial cylindrical geometry by high voltage, multi-millisecond pulses was studied by three techniques:

1. Measurement of azimuthal/axial voltage profile with high impedance voltage probes placed at a fixed radius from the center conductor.
2. Measurement of voltage profile on an array of isolated conducting cylinders placed azimuthally and axially at a fixed radius.
3. Decoration of a conducting plastic sheet placed in the earth at a fixed radius.

The results indicate:

1. In a 90° x 0.1 m long sector experiment only one streamer was formed. Its core is ≤0.3 mm in diameter at currents from 1 A to 100 A. It is surrounded by radial electric fields large enough to form Lichtenberg figures in the conducting plastic.
2. In 360° x 1 m experiments a few (<10) long streamers are observed. There is probably a high density of short streamers near the central electrode at high applied voltages.
3. While there exists some bias for very long streamers that arc-over between conductors, the location of the streamers varies from shot to shot.

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EARTH BREAKDOWN IN CYLINDRICAL GEOMETRY*
IV. MODELS

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Results of earth conduction and breakdown experiments (Ref. 1-2) suggest features of microscopic and macroscopic models of the breakdown process. Under excitation with slowly rising (rise time > 0.1 μs) electric fields, the data suggest:

1. Streamers are formed and propagate by a thermal runaway process, in which positive feedback is provided by a negative temperature coefficient of resistivity. Under long pulse excitation this process occurs at lower electric fields than the short-pulse air-cell breakdown inferred from reference 3.
2. The characteristic fields, currents and relaxation times for streamer formation and propagation are determined by the geometry and conductivity of water filaments threading through the earth sample.
3. The transition from a conducting liquid to a high current arc is not yet understood. It probably involves a negative temperature coefficient of resistivity near room temperature and a low density plasma channel in its high current state.
4. A buried cable excited to high voltage will be surrounded by a large density of short streamers, with a few long streamers. The long streamers will be extensively decorated by short branches. The resulting electric field away from the enhancement points at streamers will be $\lesssim$ 100 kV/m.

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* This work was sponsored by the Air Force Weapons Laboratory under contract F29601-78-C-0082.

1. C.E. Mallon, et al., "Electrical Breakdown Characteristics in 0.8 to 1.0 Meter MX Soil Samples", unpublished (September 1981).
2. V.A.J. van Lint, J.W. Erler, "Buried Conductor Studies", unpublished (December 1981).
3. T.M. Flanagan, et al., "Electrical Breakdown Properties of Soil", IEEE Trans. Nucl. Sci. NS-28, 4432 (December 1981).

VAPORIZATION/RESTRIKE CHARACTERISTICS OF BURIED INSULATED CONDUCTORS

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When a sufficiently large voltage pulse is applied to a metallic wire in air, it is well known that the wire will vaporize and its resistance will increase rapidly. Then, after a delay time that depends on the composition of the wire and the magnitude of the voltage pulse, a restrike arc will be generated in the metallic vapor, causing the resistance of the vaporized wire to decrease dramatically and the transmitted current to increase correspondingly until the pulser voltage decays away. However, when the conducting wire is tightly enclosed in a dielectric sheath and the resulting cable is buried in soil, it was not known what the vaporization/restrike characteristics of such cables would be, or even if a restrike would occur at all.

To study this problem, 40-cm-long test samples were constructed by attaching strips of metal, 5 mils thick and either 1/4 or 1/2 inch wide, to a 3/8-inch diameter fiberglass rod. For some samples, the strips were parallel to the axis of the rod whereas, for others, the strips were wound helically on the rod with spacings between adjacent turns. The metal was then covered with 15 mils of semicon XLP wrap followed by 280 mils of polyethylene shrunk-fit over the ensemble. The metals used in the tests were iron, aluminum, stainless steel, and Inconel 600. Voltage pulses up to 200 kV with currents greater than 100 kA were applied at the McDonnell Aircraft Lightning facility.

Depending on the magnitude of the voltage pulse, the samples vaporized and restruck in times from 5 to 50 μs. Restrikes could be generated for all sample geometries and metals, with pulser voltages sometimes as low as 60 kV across the 40 cm samples. When the tests were performed in air (no soil), the polyethylene jacket around the cable was completely shattered. When the tests were performed in soil, the vapor blew out through the dielectric in a series of holes along its length. However, the restrike characteristics were essentially identical for a given sample and voltage in air or in soil.

The restrike is significantly slower for a dielectrically confined metal compared to the same metallic configuration without an outer dielectric. The peak in the curve of resistivity versus action is considerably broader for the dielectrically wrapped cables and is a function of the applied bias. Data will also be presented comparing the different metals and cable geometries.

Effects of High Current Arcs on Insulated Wires

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We examine the potential damage caused in wires consisting of a central copper conductor surronded by polyethylene.

We present the results of a quantitative investigation of the effects of a test wave form on an insulated conductor. We find, based on the experiments and computer studies that the high-current arcs may cause erosion of the center conductor reducing the wire cross section by 30% to 50% of its original value. The polyethylene insulation suffers moderate damage in the form of a pencil-sized melt channel. High-speed motion picture film with a time resolution of 125 us shows that molten polyethylene is forced out of the hole as early as 0.5 msec by the high pressures generated. Experimental samples have clean highly resistive interior surfaces of the arc channel.

Additional knowledge about wire erosion process was gained through experiments on bare, rod-shaped electrodes. These show that molten copper is expelled from the electrodes at about 6-7 msec. The expulsion of liquid copper increases the erosion rate by an order of magnitude. This result has profound implications. It follows that the tail of the arc current plays an important role in determining the extent of electrode erosion. Erosion may be greatly enhanced if the arc current remains above 1 kA for longer than about 10 msec.

Intense arcs appear to be capable of severing a copper wire of 0.5-1 cm diameter, if they last longer than about 20-40 msec.

EMP Damage and Current Mode Second Breakdown
in Epitaxial Planar Transistors*

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EMP damage thresholds in semiconductor junction devices have been investigated much during the past decade with attention given to relatively simple thermal models and empirically determined parameters. Discrepancies between model predictions and/or a considerable spread in threshold values are evident from test results in many cases. This work reviews the mechanisms of second breakdown with presentation of computations and experimental data which shows relatively clear evidence that the current mode second breakdown (CSB) may dominate at shorter pulse widths with consequent lowering of damage threshold below that predicted by a thermal second breakdown (TSB) process.

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DAMAGE MECHANISMS FROM CURRENT DISCHARGE OF BURIED STRUCTURES

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Underground nuclear blast hardened structures often consist of an electromagnetic shield surrounded by a concrete layer. These buried structures must withstand large electromagnetic transients from EMP and lightning. This presentation addresses the potential for damage of the concrete liner due to discharge of these transients. The damage possibility occurs because the concrete-shield mechanical bond is obtained with metal studs (e.g., Nelson studs) attached to the shield. These studs with a nominal diameter and length of 1cm x 10cm concentrate electric current densities such that large local heating and mechanical expansion is obtained.

Damage criteria are developed in terms of current flow, electric field breakdown and thermal models. Current flow is modeled in terms of a quasistatic resistive network based on an electrode imbedded in a conducting media. The model includes effects of shield area, electrode shape, number of studs, a counterpoise, and the resistivity of the concrete and soil. Results are given in terms of peak current density and deposited energy density. Electric field breakdown, which is related to peak current density, is assumed to short out the volumetric resistance of the concrete or soil. Heating is related to the deposited energy, and a damage threshold is set as a local temperature rise of $100^{o}C$.

The above models provide a screen for possible mechanical damage. Results are given for various threat waveforms, shelter configurations, resistivities, and breakdown thresholds. Results are refined by two additional considerations. One is voltage clamping that inhibits initiation of adjacent arcs. The other is including energy deposition in an arc with the accompanying pressure pulse. The presentation ends with a discussion of uncertainties and areas for additional work.

TRANSIENT SCALE MODEL MEASUREMENTS FOR AIRCRAFT COUPLING ASSESSMENT*

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Electromagnetic transient measurements of scale models can serve as useful complements to full-scale tests for performing NEMP coupling assessement of military systems. For relatively modest costs, scale model tests can provide pre-test estimates and the means for evaluating the impact of modifications on coupling issues after the full-scale tests have taken place.

A 1/10 scale model of the A-7E Navy tactical aircraft has been built. The model includes all the major mechanical features both external and internal to the aircraft. Major cable bundles are modeled by representative wires routed appropriately. In this presentation, scale model and actual aircraft data will be compared. These will include both external and internal measurements.

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ON INTERACTION, DIRECT DRIVE, AND EXTRAPOLATION

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EXTRAPOLATION OF SIMULATOR TEST DATA

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We investigate several techniques which can be applied to extrapolate simulator test data for wire currents inside an enclosure with apertures to some criterion environment. Of particular interest are cases for which the wire currents depend on surface quantities (current and charge densities) of structures near the wires of interest, and for which the distribution of these surface quantities changes appreciably from a simulator environment to a threat environment. A practical example would be that of wire currents inside a airplane for the airplane in flight, when the simulator test was performed with the airplane parked on a conducting ground plane.

We illustrate the results obtainable with various extrapolation techniques by performing a gedanken experiment for a simple geometry for both a ground based and in-flight configuration and then evaluating the extrapolation techniques by comparing extrapolated results for the ground based configuration with exact results for the in-flight configuration. The simple geometry considered is that of a large, hollow cylinder having a small aperture at arbitrary locations on the cylinder, and a single wire inside the cylinder. We describe the results obtained for various lengths and termination impedances of the wire inside the cylinder, and for various locations of the aperture on the cylinder.

REFERENCE:

C. W. Harrison, Jr., and R. W. P. King, Excitation of a Coaxial Line Through a Transverse Slot, IEEE Transactions on Electromagnetic Compatability, Vol. EMC-14, No. 4, November 1972.

EXTRAPOLATION OF TRESTLE DATA

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In this paper we describe the development of the extrapolation procedure for internal response data acquired at the Trestle EMP simulator during the B-52 Baseline Test, May to October 1980. Although the simulator field amplitude decreased rapidly above 20 MHz, the spectra of many of the measured internal responses displayed well-defined resonances up to approximately 100 MHz; therefore, an extrapolation function which was usable up to high frequencies was required.

High frequency field mapping data (to 130 MHz) were obtained by numerical integration of the spectra of B-dot and D-dot measurements, and the results were spliced at about 10 MHz to low frequency data obtained using analog integrators. These composite spectra, along with the spectrum of the high altitude EMP, were used to form several trial field ratio extrapolation functions. In addition, an extrapolation function employing an analytical representation of the simulator field was developed. This analytical form was based on an expression given by Yang and Lee (AFWL Sensor and Simulation Note 267) consisting of a double-exponential and a term of the form, t exp(-at), which produces a "notch" at 3 MHz. We added two more terms: one to represent the prepulse and the other to produce the rapid drop in field amplitude above 20 MHz. For reasons which will be discussed, the analytical form was used to extrapolate the internal response data.

Extrapolated data from both Trestle and HPD for the same test points were compared in order to draw some conclusions about extrapolation uncertainties.

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A NEW LOOK AT EXTRAPOLATION TECHNIQUES

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Extrapolation techniques are typically employed to adjust the measurements made at the EMP simulators to the desired ideal EMP response. The extrapolation functions are traditionally computed in the frequency domain so that simple multiplication is needed for extrapolating the simulator response.

Several types of extrapolation (apodization) functions were introduced by Baum [1] and are the standard presently used in the community. In this paper, the weaknesses of the standard extrapolation functions, such as the phase distortion they introduce, are discussed and suggestions are made to circumvent such difficulties.

Also presented is a fresh look at the time domain convolution techniques and the possible advantage in performing the extrapolation operation entirely in the time domain.

[1] C. E. Braum, "Extrapolation Techniques for Interpreting the Results of Tests in EMP Simulators, in Terms of EMP Criteria," AFWL, SSN 222, March 1977.

THEORETICAL BASES FOR HARDNESS MONITORING

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After a system has been designed with EMP (or other electromagnetic environment) hardness in mind one optimally goes through some testing program using the best simulators and instrumentation available to determine the adequacy of the protection and make corrections where necessary. One is next faced with the problem of maintaining the system hardness. This requires some procedure for determining if and when the system hardness has unacceptably degraded, what corrective actions are needed, and the adequacy of these corrections. One approach to such a problem is to periodically subject each system to the above "complete" test program, but this would be very expensive. It would be desirable to have some simpler test procedure which would at least indicate any significant hardness degredation relative to some previous baseline condition. However, completeness of the test will be a major question. It is very important that the test procedures used be well grounded in electromagnetic theory so that they have some known quantitative relation to the criterion EMP (or other) environment.

First, one must choose some electromagnetic excitation. Two simulation concepts appear to have some significant promise: PARTES AND MEDIUS. In the PARTES concept electric and magnetic dipoles are used to synthesize the desired incident wave by spatial superposition using the field equivalence principle. Using CW excitation, norm concepts are applicable for obtaining bounds for all directions of incidence and polarization. In the MEDIUS concept electric and magnetic dipoles are combined in a special way that produces TEM fields in the $\vec{p} \times \vec{m}$ direction, even in the near field. This produces the best approximation to a CW plane wave from a small source for illuminating large areas.

Second, one must monitor the system response in a way which discovers significant hardness degredation. Basically the problem is one of completeness. If there are a large number of possibly independent failure modes the problem is very difficult, requiring in principle that all of these be monitored. If, however, one can design the system in such a manner that a relatively small number of signals control the response the problem is simplified. Electromagnetic topology can be used not only to design the system hardness, but also to design the hardness maintenance monitoring. By limiting the number of shield penetrations one can concentrate on measuring the performance of the penetration protection, both as to the existence of a penetration failure and identification of which penetration(s). Both the CW system illumination and direct penetration drive (including nonlinear time-domain effects) can be included.

EXCITATION SOURCES AND MONITOR PROBES FOR A HARDNESS ASSURANCE MONITORING SYSTEM

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Two types of electromagnetic excitation sources have been developed for HAMS. The first is an external magnetic dipole source which is individually driven to provide one-at-a-time the set of external dipoles. Two such dipole source drivers have been fabricated to cover different frequency bands of interest. The dipole moment, $\vec{m}$, of these sources is equal to their equivalent area, A_{eq}, times the current driven through them. The high frequency driver is essentially an MGL-1 sensor (1) with a small current probe built into it to monitor the input current. The low frequency souce is a multi-turn loop (2) driven differentially via a transformer. A current probe also monitors the drive current.

The second type of excitation source is a current driver used to inject current onto cable shields on the interior of the system. Transfer functions may then be measured to the interior of the cables and hardened subsystems. The current drivers are a high frequency transformer with several turns of primary winding and a single secondary turn, namely, the cable shield. A current probe adjacent to the driver is used to monitor the injected current.

A family of current probes is also available for the HAMS. These are wideband transformers with a single-turn primary, the test wire, which is coupled to the secondary by a torroidal ferrite core. This special ferrite core has excellent high frequency magnetic properties so that the upper frequency response is limited only by the physical length of the secondary winding. Typical response curves are flat to within 1 dB of the specified transfer impedance from 20 kHz to over 100 MHz.

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1. C.E. Baum, "The Multi-Gap Cylindrical Loop in Nonconductive Media", SSN 41, May 1967.

2. C.E. Baum, "Some Considerations for Electrically Small Multi-Turn Cylindrical Loops", SSN 43, May 1967.

DEVELOPMENT AND IMPLEMENTATION OF A PROTOTYPE SWEPT CW HARDNESS ASSURANCE MONITORING SYSTEM FOR THE EMP HARDENED TACAMO AIRCRAFT

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ABSTRACT

A program jointly sponsored by the Naval Surface Weapons Center, White Oak, Silver Spring, Maryland and the Air Force Weapons Laboratory, Albuquerque, New Mexico, to develop and implement a prototype swept cw Hardness Assurance Monitoring System (HAMS) for the EMP hardened EC-130G TACAMO aircraft has been recently completed. The program included development and installation of the HAMS aboard the test aircraft, baseline data acquisition during three separate, repetitive, test segments followed by extensive analysis of the test data with the objective of assessing the feasibility of a swept cw HAMS.

The test aircraft, BUNO 151891, was selected because of its two layers of EMP hardening and the large test data base which has been compiled during several EMP tests. TACAMO layer 1 hardening applies to the aircraft hull and layer 2 to hardening at mission-critical equipment rack interfaces. The prototype HAMS was based upon spectrum analyzer measurements of responses inside each hardening layer induced by swept cw stimulation applied outside each layer. Stimulation was provided by skin current drivers and cable current drivers especially developed for the purpose.

Each successive test segment was a replication of the previous one. Three sets of baseline data were acquired in addition to degraded EMP protection data. This data base has been utilized to develop analytical methods for hardness degradation detection. This paper describes the TACAMO HAMS and the HAMS test planning and test conduct.

References:

1. "Test Plan for TACAMO HAMS System Installation and Demonstration Test" 3 April, Rockwell International, C81-85/201.

2. L. Marin, and F. M. Tesche, "Topological and Physical Description of TACAMO Hardness Assurance Monitoring System," report submitted to Rockwell International for Contract N60921-81-C-0145, April 1981.

3. "TACAMO Hardness Assurance Monitoring System (HAMS) Preliminary Test Report," September 25, 1981, Rockwell International, C81-646/201.

4. "TACAMO Hardness Assurance Monitoring System (HAMS) Final Test Report," 17 November 1981, Rockwell International, C81-739/201.

REDUCTION SCHEMES FOR
TACAMO HAMS DATA

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The TACAMO HAMS system is a prototype swept CW system intended to measure any degradations in the integrity of the TACAMO EMP protection measures. The data were acquired at three different test occasions with drivers and monitors placed at various locations on the aircraft.

The methods used to reduce the raw data to single scalar numbers will be discussed. These methods are based on energy and correlation quantities in different bands. The capability of the methods of distinguishing different aircraft responses will be discussed. The reduced data will also be used to draw some conclusions about the capabilities of the present HAMS system and make recommendations for possible future systems.

DATA PROCESSING FOR A HARDNESS ASSURANCE MONITORING SYSTEM (HAMS) BASED ON FUNCTIONAL COMPARISONS OF MEASURED DATA

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ABSTRACT

A current problem of interest in assuring the survivability of a weapons system in a nuclear EMP environment is that of developing an onboard monitoring device which can periodically determine whether the EMP hardness of the system is adequate. Initially, such a system may have a high degree of hardness, but during the life cycle of the system, the hardness may degrade due to aging of components or routine maintenance. Unless periodic tests are performed to monitor the hardness, there is no assurance that the system will perform as desired.

Recently, a feasibility study of a hardness assurance monitoring system (HAMS) located within an aircraft was undertaken. This involved installing skin current drivers on the exterior of the aircraft, and current drivers on selected cables within the interior. Swept CW measurements in the .1 to 100 MHz range for the induced currents on internal cabling were then made for various driver/sensor combinations. Both the hardened (baseline) configuration and deliberately degraded shielding configurations of the aircraft were considered in order to determine the sensitivity of the measurements to the state of the electromagnetic shields within the system.

One important aspect of a HAMS system is how the acquired data is processed in order to determine whether or not there is a fault in the shielding. Ideally, one would like a simple scalar number which indicates how closely a measurement made during a test compares with the same measurement made when the system was "known" to be hard. Since the measurements are really functions (i.e., the swept CW response of the current over a particular frequency range), there are a number of methods of determining a simple scalar quantity which compares the two data records.

Alternatively, one can conceive of comparing HAMS data records on a functional basis by looking at cross correlation functions, Fourier transforms, and the like. Although this does not add any additional information into the measured data, it does provide a different way of looking at the data and possibly detecting system shielding faults.

This paper will discuss the various HAMS data taken during this test, and will illustrate the different functional data comparison schemes which were used to investigate the feasibility of this monitoring concept.