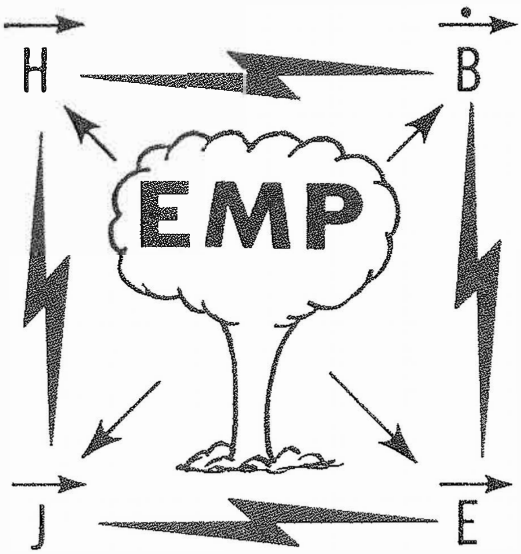
1260

# JOINT EMP TECHNICAL MEETING
# FIRST ANNUAL NUCLEAR EMP MEETING

# NEM 1973

## ABSTRACTS OF TECHNICAL PAPERS

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Welcome to the 1973 Joint EMP Technical Meeting. Judging from the number of authors who submitted papers and the requests for invitations to attend this meeting, it appears that there exists the better part of one thousand people who devote some considerable amount of their time and attention to EMP as a scientific and engineering discipline. We have endeavored to bring a large number of the workers in the field together and have accepted papers from approximately 300 authors. Unfortunately, we did have to limit attendance to approximately 550 people based on the physical plant available. As with many subjects as they grow we have had to go to many parallel sessions in order to handle what appear to be a large number of acceptable papers. The meeting is jointly sponsored by the Army, the Navy, the Air Force and the Defense Nuclear Agency, who have worked with myself and the rest of the conference staff through the Advisory Group, chaired by Mr. Ron Bostak of HDL. In addition, we have sought a cross section of the technical workers in the field to play a major role in the shaping of the technical aspects of this program through the formation of a Technical Steering Committee, chaired by Dr. Carl E. Baum of AFWL. This latter group has been responsible for selection of papers and the invited state-of-the-art papers. On behalf of all of the parties who have labored to put this meeting together, I again welcome you, and hope that you have a profitable interchange.

John Darrah

JOHN H. DARRAH, Conference Chairman

## ACKNOWLEDGEMENT

The chairman is grateful to the following committees for their hard work in support of this conference. It would not have been possible without their assistance.

### Technical Steering Committee

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JOINT EMP TECHNICAL MEETING
25 - 27 September 1973
Kirtland AFB NM

| | |
|---|---|
| 0800-0900 | Registration and Security<br>Badging, Bldg 485, Kirtland AFB West Theater |
| 0900-1000 | Welcome<br>Commander, AFWL<br><br>General Session<br>Opening Remarks<br>Chairman<br><br>BG Jasper A. Welch, Special Asst to the Asst to the Sec of Def for Atomic Energy<br>"Considerations in Establishing Criteria for Nuclear Survivability" |
| 1000-1030 | Break |
| 1030-1200 | Dr. Kenneth L. Jordan, Jr., Dir Strategic and Space Systems ODASD/Systems, OASD(T)<br><br>Col Wallace D. Henderson, Special Asst for Warning to ASD(I)<br>"Current and Future Warning Systems (Strategic and Tactical) vs. Nuclear Weapons Effects" |

## GUIDELINES FOR TABLE OF CONTENTS

Technical papers presented at the Joint EMP Technical Meeting are identified within the digest of abstracts by a page number and a paper number. Each paper is assigned a number corresponding to its order of presentation within its appropriate session.

Paper titles along with corresponding paper and page numbers are listed by section in the Table of Contents. Each paper is assigned a unique three digit identifier called the Paper No. (X-Y-Z).

X is the section number of the paper
Y is the session number of the paper
Z is the order in which the paper will be presented within its session

| SECTION NO. | SESSION NO. | TITLE & CLASS. | DATE | TIME | BLDG NO. | CONF. RCOM NO. | KAFB |
|---|---|---|---|---|---|---|---|
| 1 | | Environment | | | | | |
| | 1-1A | Ground Burst Environments and Close-In Coupling(SRD) | 25Sep | 1330-1439 | 497 | 1 | West |
| | 1-1B | Ground Burst Environments and Close-In Coupling(U) | 25Sep | 1500-1700 | 497 | 1 | West |
| | 1-2 | Exoatmospheric EMP and Selected Topics(SRD) | 26Sep | 0830-1000<br>1030-1200 | 497 | 1 | West |
| | 1-3A | High Altitude EMP Environments(SRD) | 26Sep | 1330-1514 | 497 | 1 | West |
| | 1-3B | High Altitude EMP Environments(U) | 26Sep | 1545-1650 | 497 | 1 | West |
| | 1-4A | System Generated EMP(SRD) | 27Sep | 0830-1015 | 497 | 1 | West |
| | 1-4B | System Generated EMP(U) | 27Sep | 1045-1200 | 497 | 1 | West |
| 2 | | Instrumentation | | | | | |
| | 2-1A | Single Transient A-D Techniques and Data Reduction(U) | 26Sep | 0830-1000 | 363 | Main | East |
| | 2-1B | EMP Sensors(U) | 26Sep | 1030-1200 | 363 | Main | East |
| | 2-2 | Measurement Techniques and Data Transmission(U) | 27Sep | 1330-1430<br>1500-1645 | 485 | | West |
| 3 | | Interaction | | | | | |
| | 3-1A | Coupling into Apertures(U) | 25Sep | 1330-1515 | 485 | | West |
| | 3-1B | Coupling into Cables(U) | 25Sep | 1545-1715 | 485 | | West |
| | 3-2A | Coupling to Power Lines(U) | 26Sep | 0830-1000 | 485 | | West |
| | 3-2B | Coupling to Multiconductor Transmission Lines(U) | 26Sep | 1030-1200 | 485 | | West |
| | 3-3A | Invited Papers(U) | 26Sep | 1330-1430 | 485 | | West |

| SECTION NO. | SESSION NO. | TITLE & CLASS. | DATE | TIME | BLDG NO. | CONF. ROOM NO. | KAFB |
|---|---|---|---|---|---|---|---|
| | 3-3B | Coupling to Horn Antennas(U) | 26Sep | 1430-1500 | 485 | | West |
| | 3-3C | Coupling into Antennas(U) | 26Sep | 1330-1715 | 485 | | West |
| | 3-4A | External Coupling of Aircraft(U) | 27Sep | 0830-1000 | 485 | | West |
| | 3-4B | External Coupling of Missile-Like Structures(U) | 27Sep | 1030-1215 | 485 | | West |
| 4 | | Simulation Technology | | | | | |
| | 4-1A | Simulator Structures - Radiators(U) | 25Sep | 1330-1500 | 363 | Main | East |
| | 4-1B | Simulator Structures - Hybrid Simulators(U) | 25Sep | 1530-1700 | 363 | Main | East |
| | 4-2A | Simulator Structures - Parallel Plates I(U) | 26Sep | 1330-1500 | 363 | Main | East |
| | 4-2B | Simulator Structures - Parallel Plates II(U) | 26Sep | 1530-1645 | 363 | Main | East |
| | 4-3A | Simulator Pulsers(U) | 27Sep | 0830-1000<br>1030-1115 | 363 | Main | East |
| | 4-3B | SGEMP Simulation I(U) | 27Sep | 1115-1145 | 363 | Main | East |
| | 4-4A | SGEMP Simulation II(U) | 27Sep | 1330-1445 | 363 | Main | East |
| | 4-4B | Simulator Specifications, Measurements, and Testing(U) | 27Sep | 1515-1700 | 363 | Main | East |
| 5 | | Hardening Technology | | | | | |
| | 5-1A | General Hardening Techniques(U) | 26Sep | 0830-1000<br>1030-1130 | 414 | 3 | West |
| | 5-1B | Protective Devices I(U) | 26Sep | 1130-1215 | 414 | 3 | West |
| | 5-2A | Protective Devices II(U) | 26Sep | 1330-1445 | 414 | 3 | West |

| SECTION NO. | SESSION NO. | TITLE & CLASS. | DATE | TIME | BLDG NO. | CONF. ROOM NO. | KAFB |
|---|---|---|---|---|---|---|---|
| | 5-2B | Effects of EMP Transients on Semiconductor Devices(U) | 26Sep | 1515-1700 | 414 | 3 | West |
| | 5-3A | EMP Hardening Techniques(U) | 27Sep | 1330-1400 | 414 | 3 | West |
| | 5-3B | EMP Interaction Techniques/ Shielding(U) | 27Sep | 1400-1500<br>1530-1700 | 414 | 3 | West |
| 6 | | System Level Considerations | | | | | |
| | 6-1 | System-Level Considerations for Ground and Ocean Systems(U) | 25Sep | 1330-1508<br>1538-1735 | 414 | 3 | West |
| | 6-2 | Aircraft and Missile System-Level Considerations(U) | 27Sep | 0830-1002<br>1030-1229 | 414 | 3 | West |
| C | | Combined Classified Session | | | | | |
| | C-1A | Selected EMP System-Level Considerations (SRD) | 27Sep | 1330-1515 | 497 | 1 | West |
| | C-1B | Selected EMP Interaction and Hardening Subjects(SRD) | 27Sep | 1545-1715 | 497 | 1 | West |

1. ENVIRONMENT SECTION - Page 48

Chairman: Dr. William J. Karzas
R&D Associates

25 Sep 73, 1:30pm - 5:00pm, Bldg 413, Conf Rm 1, West

GROUND BURST ENVIRONMENTS AND CLOSE-IN COUPLING
CHAIRMAN: DR. W. E. PAGE, AFWL
ENVIRONMENT SECTION 1, SESSION 1

Section 1, Session 1, Continued

26 Sep 73, 8:30am - 12:00am, Bldg 413, Conf Rm 1, West

EXOATMOSPHERIC EMP AND SELECTED TOPICS
CHAIRMAN: W. A. RADASKY, MISSION RESEARCH CORP.
ENVIRONMENT SECTION 1, SESSION 2

26 Sep 73, 1:30pm - 5:00pm, Bldg 413, Conf Rm 1, West

HIGH ALTITUDE EMP ENVIRONMENTS
CHAIRMAN: W. T. WYATT, HARRY DIAMOND LABORATORY
ENVIRONMENT SECTION 1, SESSION 3

Section 1, Session 3, Continued

27 Sep 73, 8:30am - 12:00am, Bldg 413, Conf Rm 1, West

SYSTEM GENERATED EMP
CHAIRMAN: RICHARD R. SCHAEFER, R&D ASSOCIATES
ENVIRONMENT SECTION 1, SESSION 4

Section 1, Session 4, Continued

2. INSTRUMENTATION SECTION - Page 106

Chairman: Ralph Partridge
Los Alamos Scientific Laboratory

26 Sep 73, 8:30am - 12:00am, Bldg 363, DNA Conf Rm, East

SINGLE TRANSIENT A-D TECHNIQUES AND DATA REDUCTION

CHAIRMAN: KEITH TREECE, SANDIA CORP.

INSTRUMENTATION: SECTION 2, SESSION 1A

26 Sep 73, 8:30am - 12:00am, Bldg 363, DNA Conf Rm, East

EMP SENSORS
CHAIRMAN: RALPH PARTRIDGE, LASL
INSTRUMENTATION: SECTION 2, SESSION 1B

27 Sep 73, 1:30pm - 5:00pm, Bldg 485, Kirtland AFB West Theater

MEASUREMENT TECHNIQUES AND DATA TRANSMISSION
CHAIRMAN: DON FORRESTER, EG&G, INC.
INSTRUMENTATION: SECTION 2, SESSION 2

3. INTERACTION SECTION - Page 133

Chairman: Clayborne Taylor
Mississippi State University

25 Sep 73, 1:30pm - 5:00pm, Bldg 485, Kirtland AFB West Theater

COUPLING INTO APERTURES
CHAIRMAN: R. MITTRA, UNIVERSITY OF ILLINOIS
INTERACTION SECTION 3, SESSION 1A

25 Sep 73, 1:30pm - 5:00pm, Bldg 485, Kirtland AFB West Tueater

COUPLING INTO CABLES
CHAIRMAN: J. BOMBARDT, HARRY DIAMOND LABORATORIES
INTERACTION SECTION 3, SESSION 1B

26 Sep 73, 8:30am - 12:00am, Bldg 485, Kirtland AFB West Theater

COUPLING TO POWER LINES
CHAIRMAN: P. RANDY BARNES, OAK RIDGE NATIONAL LAB
INTERACTION SECTION 3, SESSION 2A

26 Sep 73, 8:30am - 12:00am, Bldg 485, Kirtland AFB West Theater

COUPLING TO MULTICONDUCTOR TRANSMISSION LINES
CHAIRMAN: FRED TESCHE, SAI
INTERACTION SECTION 3, SESSION 2B

26 Sep 73, 1:30pm - 5:00pm, Bldg 485, Kirtland AFB West Theater

INVITED PAPERS
CHAIRMAN: E. K. MILLER, LAWRENCE LIVERMORE LABORATORIES
INTERACTION SECTION 3, SESSION 3A

26 Sep 73, 1:30pm - 5:00pm, Bldg 485, Kirtland AFB West Theater

COUPLING TO HORN ANTENNAS
CHAIRMAN: E. K. MILLER, LLL
INTERACTION SECTION 3, SESSION 3B

26 Sep 73, 1:30pm - 5:00pm, Bldg 485, Kirtland AFB West Theater

COUPLING INTO ANTENNAS
CHAIRMAN: C. W. HARRISON, JR., GENERAL ELECTRO-MAGNETICS
INTERACTION SECTION 3, SESSION 3C

27 Sep 73, 8:30am - 12:00am, Bldg 485, Kirtland AFB West Theater

EXTERNAL COUPLING OF AIRCRAFT
CHAIRMAN: DR. LEON PETERS, OHIO STATE UNIVERSITY
INTERACTION SECTION 3, SESSION 4A

27 Sep 73, 8:30am - 12:00am, Bldg 485, Kirtland AFB West Theater

EXTERNAL COUPLING OF MISSILE-LIKE STRUCTURES
CHAIRMAN: LOU LIBELLO, NOL
INTERACTION SECTION 3, SESSION 4B

27 Sep 73, 1:30pm - 5:00pm, Bldg 413, Conf Rm 1, West

SELECTED EMP INTERACTION AND HARDENING SUBJECTS
CHAIRMAN: D. MEREWETHER, MRC
CLASSIFIED SESSION C-1B

4. SIMULATION TECHNOLOGY SECTION - Page 199

Chairman: John C. Martin
Atomic Weapons Research Establishment
Aldermaston, Reading, England

25 Sep 73, 1:30pm - 5:00pm, Bldg 363, DNA Conf Rm, East

SIMULATOR STRUCTURES - RADIATORS
CHAIRMAN: R. W. LATHAM, NORTHROP CORPORATE LABS
SIMULATION TECHNOLOGY: SECTION 4, SESSION 1A

25 Sep 73, 1:30;m - 5:00pm, Bldg 363, DNA Conf Rm, East

SIMULATOR STRUCTURES - HYBRID SIMULATORS
CHAIRMAN: LENNART MARIN, THE DIKEWOOD CORP.
SIMULATION TECHNOLOGY: SECTION 4, SESSION 1B

26 Sep 73, 1:30pm - 5:00pm, Bldg 363, DNA Conf Rm, East

SIMULATOR STRUCTURES - PARALLEL PLATES
CHAIRMAN: DIPAK L. SENGUPTA, UNIVERSITY OF MICHIGAN
SIMULATION TECHNOLOGY: SECTION 4, SESSION 2A

26 Sep 73, 1:30pm - 5:00pm, Bldg 363, DNA Conf Rm, East

SIMULATOR STRUCTURES - PARALLEL PLATES
CHAIRMAN: DAN F. HIGGINS, MISSION RESEARCH CORP.
SIMULATION TECHNOLOGY: SECTION 4, SESSION 2B

27 Sep 73, 8:30am - 12:00am, Bldg 363, DNA Conf Rm, East

SIMULATOR PULSERS
CHAIRMAN: IAN SMITH, PHYSICS INTERNATIONAL
SIMULATION TECHNOLOGY: SECTION 4, SESSION 3A

27 Sep 73, 8:30am - 12:00am, Bldg 363, DNA Conf Rm, East

SGEMP SIMULATION I
CHAIRMAN: K. S. H. LEE, THE DIKEWOOD CORP.
SIMULATION TECHNOLOGY: SECTION 4, SESSION 3B

27 Sep 73, 1:30pm - 5:00pm, Bldg 363, DNA Conf Rm, East

SGEMP SIMULATION II
CHAIRMAN: K. S. H. LEE, THE DIKEWOOD CORP.
SIMULATION TECHNOLOGY: SECTION 4, SESSION 4A

27 Sep 73, 1:30pm - 5:00pm, Bldg 363, DNA Conf Rm, East

SIMULATOR SPECIFICATIONS, MEASUREMENTS AND TESTING
CHAIRMAN: WALT WARE, KAMAN SCIENCES CORP.
SIMULATION TECHNOLOGY: SECTION 4, SESSION 4B

SELECTED EMP SYSTEM-LEVEL CONSIDERATIONS
CHAIRMAN: A. A. COOPER, SANDIA LABORATORIES
CLASSIFIED SESSION C-1A

5. HARDENING TECHNOLOGY - Page 256

Chairman: Jere Dando
Harry Diamond Laboratory

26 Sep 73, 8:30am - 12:00am, Bldg 414, Conf Rm 3, West

GENERAL HARDENING TECHNIQUES
CHAIRMAN: ROBERT POHL, R&D ASSOCIATES
HARDENING TECHNOLOGY: SECTION 5, SESSION 1A

26 Sep 73, 8:30am - 12:00am, Bldg 414, Conf Rm 3, West

PROTECTIVE DEVICES I
CHAIRMAN: BOB POHL, R&D ASSOCIATES
HARDENING TECHNOLOGY: SECTION 5, SESSION 1B

26 Sep 73, 1:30pm - 5:00pm, Bldg 414, Conf Rm 3, West

PROTECTION DEVICES II

CHAIRMAN: VIC VANLINT, INTELCOM RAD TECH

HARDENING TECHNOLOGY: SECTION 5, SESSION 2A

26 Sep 73, 1:30pm - 5:00pm, Bldg 414, Conf Rm 3, West

EFFECTS OF EMP TRANSIENTS ON SEMICONDUCTOR DEVICES
CHAIRMAN: VICTOR VAN LINT, INTELCOM RAD TECH
HARDENING TECHNOLOGY: SECTION 5, SESSION 2B

27 Sep 73, 1:30pm - 5:00pm, Bldg 414, Conf Rm 3, West

EMP HARDENING TECHNIQUES
CHAIRMAN: BYRON GAGE, BOEING AEROSPACE COMPANY
HARDENING TECHNOLOGY: SECTION 5, SESSION 3A

27 Sep 73, 1:30pm - 5:00pm, Bldg 414, Conf Rm 3, Weat

EMP INTERACTION TECHNIQUES/SHIELDING
CHAIRMAN: BYRON GAGE, BOEING AEROSPACE CO.
HARDENING TECHNOLOGY: SECTION 5, SESSION 3B

27 Sep 73, 1:30pm - 5:00pm, Bldg 413, Conf Rm 1, West

SELECTED EMP INTERACTION AND HARDENING SUBJECTS
CHAIRMAN: D. MEREWETHER, MISSION RESEARCH CORPORATION
CLASSIFIED SESSION C-1B

6. SYSTEM LEVEL CONSIDERATIONS SECTION - Page 302

Chairman: Dr. William R. Graham, Jr.
R&D Associates

25 Sep 73, 1:30pm - 5:00pm, Bldg 414, Conf Rm 3, West

SYSTEM-LEVEL CONSIDERATIONS FOR GROUND AND OCEAN SYSTEMS
CHAIRMAN: DR. WILLIAM R. GRAHAM, JR., R&D ASSOCIATES
SYSTEM LEVEL CONSIDERATIONS: SECTION 6, SESSION 1

Section 6, Session 1 (Cont'd)

27 Sep 73, 8:30am - 12:00am, Bldg 414, Conf Rm 3, West

AIRCRAFT AND MISSILE SYSTEM-LEVEL CONSIDERATIONS
CHAIRMAN: MAJ WILLIAM ADAMS, DNA
SYSTEM LEVEL CONSIDERATIONS: SECTION 6, SESSION 2

27 Sep 73, 1:30pm - 5:00pm, Bldg 413, Conf Rm 1, West

SELECTED EMP SYSTEM-LEVEL CONSIDERATIONS
CHAIRMAN: A. A. COOPER, SANDIA LABORATORIES
CLASSIFIED SESSION C-1A

# ENVIRONMENT SECTION

ENVIRONMENT SECTION

Session 1

Tuesday Afternoon 25 September 1973

Chairman: Dr. William E. Page
Air Force Weapons Laboratory

1-1-1

# DEVELOPMENTS IN EMP THEORIES

Dr. Conrad Longmire
Mission Research Corporation

This paper is a brief discussion of recent advances in capabilities for calculating EMP environment from nuclear explosions at low and high altitude in the atmosphere, together with a summary of current developments and outstanding problems.

1-1-2

# GLANC-Physics and Results

Robert M. Hamilton, Robert N. Marks, William A. Radasky
Mission Research Corporation

GLANC is a computer code for obtaining the solution, by finite difference methods, of Maxwell's equations in one space dimension and retarded time, for the electromagnetic fields produced by a nuclear burst near or on the ground. The fields are calculated in the air, in the ground, and on the ground-air interface. The approximations in GLANC are such that the field calculations are valid for early times and for distances less than about one kilometer; however, another version of the code, called GLANC-L, utilizes expanding space and time meshes to compute the fields to approximately 10 μsec. The yield of the nuclear device determines the maximum distance for which the approximations are valid. The field components considered are $B_x$, $E_z$, and $E_y$ in rectangular coordinates. In the ground the electrical conductivity is normal constant in time and space. The source (Compton) current in the ground can be different from zero to zero. The ground current is always set to zero when the height of the nuclear burst above the ground is zero. The conductivity in the air is found by solving the "air-ion" equations, which take account of gamma-induced ionization, electron attachment to $O_2$, and electron-ion and ion-ion recombination. Transport of gamma rays in the air is handled by prescription, using attenuation lengths and buildup factors. The sources in the air for the currents and ionization are determined by any of three methods: (1) injection of Compton electrons and solution of their equations of motion; (2) using the LEMP fits to Compton current and ionization rate as function of the fields; (3) by simply making the Compton current and ionization rate proportional to the gamma flux, without field reaction. GLANC-L, the late time code, calculates the sources in the air using either (2) or (3) above.

GLANC-Physics and Results (Cont'd)

Calculations from the one-dimensional low-altitude EMP code, GLANC, are presented. Close-in predictions are illustrated including self-consistency. The ability of GLANC-L to calculate to late-times is also described. The effect of considering X-ray and neutron ionization in the calculations is shown from a comparison point of view.

1-1-3

# LEMP-1--Physics and Results

William A. Radasky, Conrad L. Longmire, H. Jerry Longley

Mission Research Corporation

LEMP-1 is a computer code for obtaining the solution, by finite difference methods, of Maxwell's equations in two space dimensions and retarded time, for the electromagnetic fields produced by a nuclear burst on the ground. The field components considered are $B_\Phi$, $E_\theta$, and $E_r$ in the usual spherical coordinates. These fields are calculated in the air, in the ground, and on the ground-air interface. In the ground the electrical conductivity is constant in time and space, and the source current is zero. The conductivity in the air is found by solving the "air-ion" equations, which take account of gamma-induced ionization, electron attachment to $O_2$, and electron-ion and ion-ion recombination. The source current in the air is the Compton recoil current produced by gamma rays, the source and transport of which are given by a fairly general and flexible prescription. The back-action of the fields on the air conductivity and the source current is treated. The output from LEMP-1 can be used in a separate subroutine to calculate the fields deep in the ground. This subroutine, which accounts for the frequency-dependence of the ground parameters (conductivity and dielectric constant), solves the electromagnetic problem in the time-domain. Calculations from the two-dimensional ground burst EMP code, LEMP-1, are presented. Selected waveforms from the LEMP-1 library are shown

including more recent LEMP-1 calculations. Special attention is given to the vertical currents and fields enhanced by the self-consistent treatment of Compton electrons.

1-1-4

# GROUND BURST EMP

S. J. Dalich
Science Applications, Inc.

Capt J. Morgan
Air Force Weapons Laboratory

Results of calculations using the SCX Code, a two-dimensional ground burst EMP code, are presented. The results are presented in both the time and frequency domains. The assumptions, approximations, and sources used in obtaining these results are discussed. This discussion includes effects considered in obtaining both gamma and neutron induced sources, as well as assumptions concerning weapon parameters.

# THE LATE-TIME EMP ENVIRONMENT

E. R. Parkinson
SAI

W. R. Graham
R&D Associates

An approximate method for predicting the late-time above ground EMP environment produced close to a near-surface nuclear explosion is described. The method permits the use of independent general time and space-dependent distributions of current and conductivity, subject only to the constraint of azimuthal symmetry about the burst point.

The initial conditions for the late-time solution can be obtained from early-time field predictions such as those produced by the two dimensional explicit finite difference code SC.

The advantage of the method described in this paper over explicit finite difference techniques is primarily one of calculational feasibility. For reasons of numerical stability, the maximum time increment $\Delta t$ permissible with finite differencing techniques is generally limited by the Courant condition

$$\Delta t/\Delta x < 1/c,$$

where $\Delta x$ is the space increment and c is the speed of light. The method described in this paper uses a numerical method that is entirely implicit, and time increments are not limited by the Courant condition, making the use of large time steps possible. Accuracy is not sacrificed by using these large time steps, since the values of the fields change only slowly at late times.

Predictions of the implicit method have been compared with an analytical solution developed previously for an analytically convenient current and conductivity distribution. Fields which have been calculated to a time on the order of one second using more realistic source distributions are discussed.

For the present calculation, the simplifying physical assumption that late-time fields are determined by a field diffusion process in which conduction currents dominate displacement currents is made.

# ONE-DIMENSIONAL, CLOSE-IN, SELF-CONSISTENT, GAMMA-INDUCED EMP FIELDS: PRELIMINARY RESULTS

Chris W. Jones
The Dikewood Corporation

Preliminary results of CLASP (Close-In, Low-Altitude, Self-Consistent Pulse) are presented which show the effects of self-consistency on close-in, gamma-induced EMP fields. CLASP allows for a completely self-consistent treatment of the Compton electrons in a close-in environment. The multiple scattering of the Compton electrons may be treated either by an obliquity factor or by the random selection of scattering angles from the expected scattering distribution. Results are also included which show the effect of the inclusion of electron-ion scattering effects in the calculation of electron mobility in close-in calculations.

1-1-7

# NEAR SURFACE BURST

E. R. Parkinson and R. C. Knight
Science Applications, Inc.

A near surface burst code, presently being developed, will be discussed. Important considerations include choice of coordinate system, the form of the E. M. field equations, the differencing scheme applied to the field equations, and the boundary conditions to be imposed. A number of choices appear feasible in each of these areas, and certain alternatives will be compared. The requirements that are expected to be most significant in determining the approach finally adopted include accurate handling of ground reflections, inclusion of dielectric and conductivity structure in the earth and air, and compatibility with far-field extrapolation schemes.

1-1-8

# ESTIMATION OF INDUCED SURFACE CURRENTS FROM A CLOSE-IN BURST *

Roger C. Kennedy
Boeing Aerospace Co., P. O. Box 3999
Seattle, Washington 98124

Abstract - Section c. Unclassified

An approximation is discussed by which estimates can be simply made of currents induced on metallic bodies from a close-in nuclear burst. The approximation assumes a fast-rising electric field followed by a gamma-ray induced air conductivity. The diffusion approximation is applied to Maxwell's equations, and after a simple transformation on the time ariable, the diffusion equation takes on a simple form. Initial value conditions are ignored and the current time-history results entirely from boundary conditions. For the situation considered here, skin depths become small enough so that the boundary conditions appropriate to a plane are applied. The resulting expression for the induced current has been compared with more complete calculations for a sphere. Some numerical examples are presented to illustrate this comparison.

* This work was performed under contract F04701-70-C-0137.

1-1-9

# CLOSE-IN POWER LINE COUPLING

Kurt A. Graf
Stanford Research Institute
Menlo Park, California

Calculations have been made to evaluate EMP coupling to power lines when air conductivity effects are important. The plasma distribution along the power line was considered to vary spatially and temporally, so it was not possible to obtain analytic solutions for situations of interest. A computer program was developed that provided simultaneous numerical solution of two first-order differential equations describing the spatial and temporal variation of current and voltage on the non-uniform transmission line. In the calculation, the parameters of the line, and the incident coupling signal were varied spatially and temporally. Calculations have been made showing coupling to a lossy transmission line for a number of cases of interest. In one set of calculations, the line was considered located from 800 m to 2000 m from a ground burst, and the signal through a load 2000 m from the burst was determined. It was found that the peak signal through a load 2000 m from a ground burst was influenced primarilly by the portion of the power line on which the peak electron density was less than about $10^{10}$ $cm^{-3}$ (the corresponding conductivity was $10^{-3}$ mhos/m). Thus for all practical purposes, it is valid when calculating coupling to concentrate on the "far" and intermediate" zones, and ignore the "near" zone where electron densities are much larger.

Y. B. Yu, Communication and Systems Division, GTE Sylvania, 189 "B" Street Needham Height, MA 02194.

R. S. Chu, Advanced Development Laboratory, Equipment Division, Raytheon Company, Wayland, MA.

J. H. Terrell, Thermo Magnetics, Inc., Woburn, MA.

Excitation and Propagation of a Signal Between Two High Leakage Transmission lines with Time Dependent Inductances and Conductances.*

## ABSTRACT

We present a model for the excitation and propagation of a signal on a high leakage transmission line with time dependent inductance ($L(t)$) and conductance ( $G(t)$ ). A current source uniformly excites a length of the line (known as line 1) whose environment is represented by $L_1(t)$ and $G_1(t)$. Line 1 is open-ended to the left and terminates at a junction beyond which the environment is characterized by $L_2(t)$ and $G_2(t)$. This part of the line (known as line 2) extends from the junction to infinity. Since line 1 is a high leakage line, the effect of the double reflected voltage and current into the junction can be neglected. (Double reflected here means that the reflected voltage and current at the junction travels backward to the open end and is reflected by the open end to the junction again). This permits us to make the calculation in 4 steps: (1) Solve the incident voltage and current for an open-ended semi-infinite line with a uniformly distributed current source up to the junction to the right; (2) Solve for the reflected voltage and current at the junction in terms of a semi-infinite line to the left; (3) Find the voltage and current for line 2 considered to be a semi-infinite line to the right; (4) Match boundary condition at the junction of line 1 and 2.

In the nuclear detonation environment, the problems of coupling the radiations into the electronic systems frequently come up with this kind of transmission lines. As examples, we apply the results to the problems of the above ground power line subject to the EMP and IEMP excitations, and the current flowing on the LF ground strap following X-ray excitation on the security antenna housing.

* Work has been done at the GTE Sylvania

1-1-11

Cheng Meng Wu

GTE SYLVANIA COMMUNICATION SYSTEMS DIVISION

ABSTRACT: POWER LINE PENETRATIONS IN A NUCLEAR ENVIRONMENT

This paper describes calculations to predict the voltages at the input to a facility from a nuclear environment (normalized ground burst) on the primary power penetration. A typical-site power-line entry configuration with the resulting "loops" and the conduits associated with the local take-off at the facility penetration was used. It was modeled as a time-varying lumped-parameter network driven by EMP source voltages along the line and IEMP source currents within the conduit.

The main feature of the paper is the treatment of the ionized air effects as a plasma line whose node position changes with time as the air conductivity changes during the threat pulse.

The calculations consider several directions of arrival of the nuclear threat, both non-ionized and ionized insulated wire, and the conductivity of the air inside the conduit. Details of the model and of the calculations are given. Results are plotted for easy interpretation and comparison, to show the relative importance of the various sources.

1-1-12

David P. Flood - John Terrell
GTE SYLVANIA COMMUNICATION SYSTEMS DIVISION

ABSTRACT: CLOSE-IN COUPLING EFFECTS ON SITE-TYPICAL CONFIGURATIONS

This paper discusses the predicted coupling to buried and above-ground structures from the radiation components of a close-in nuclear event. Several generic models are described which encompass typical structures, conduits, and cables at hardened installations. The computations make use of a variety of closed form and numerical integration techniques.

Coupling levels are predicted based on environmental levels of exposure. Current and voltage waveforms are shown for representative configuration which include:

a) buried insulated conductors
b) exposed conduits with power wiring
c) wiring fixture boxes
d) exposed high-voltage power lines

Orders of magnitude are shown for evaluation with field pickup effects.

1-1-13

# Theoretical Analysis of a Conducting Body Immersed in an EMP Source Region

Charles Tse Chin Mo

R & D Associates
Santa Monica, California 90403

## ABSTRACT

We investigated the problem of a conducting body immersed in air and illuminated by a $\gamma$-ray flux. In this EMP source coupling region, the charge, the current, and the field at the conducting body are of interest. We formulate a scheme of solving this problem by carefully decomposing the problem into its various basic aspects concerning the effects of the incident $\gamma$-rays only, of the driving Compton electron current, and of the ionized air conductivity. Each effect is separately examined and their combined effects when put together are obtained.

Then a simple special case concerning an infinitely-conducting and infinitely-dense finite cylinder illuminated by a "steady" stream of $\gamma$-rays is solved. This provides physical insights into the EMP source region effects and illustrates the scheme of theoretical analysis for more complex problems.

ENVIRONMENT SECTION

**Session 2**

Wednesday Morning 26 September 1973

**Chairman:** W. A. Radasky
Mission Research Corporation

1-2-1

# Non-Linear Propagation of Satellite EMP in the D-Region of the Ionosphere

Lt William A. Seidler, II and Capt Gary Knutson
Air Force Weapons Laboratory

The D-region of the ionosphere has been found to act as a high pass filter. The high altitude EMP produces electron heating in the D-region, increasing the collision frequency. This produces an absorptive mechanism for low frequencies. A Boltzman formulation is solved self-consistently with the one-dimensional wave equation. Discussion of the parameters of the model, applicability of the model, and results for a "worst case" environment will be presented.

1-2-2

# PROPAGATED EMP FROM TANGENT BURSTS

Capt G. H. Canavan
Capt L. A. Wittwer
Capt J. E. Brau
1Lt A. E. Greene
Air Force Weapons Laboratory

Tangent bursts are high altitude events in which the gammas directed just above the earth's limb, in descending through air of higher density, produce a radiated EM pulse which propagates out through the ionosphere on the other side of the point of tangency. The threat calculations reported here are based on the AFWL CHEMP code[1] for self-consistent calculations or radiated EMP, modified by the inclusion of a swarn treatment[2] of secondary and ionospheric electrons. The region of applicability of this swarm treatment has been determined by a separate M-C calculation. By carrying the calculations all the way from the burst point, down into the source region, and back into the E region on the way out we are able to account fully for the D region heating, the increased absorption and cascading it produces, and the increased cutoff frequency which results. The code calculations are compared with analytic treatments, and are evaluated for sensitivity to the ambient ionospheres used.

1. L. A. Wittwer, J. E. Brau, G. H. Canavan "CHEMP: A Code for Self-Consistent Calculations of High Altitude EMP" AFWL/DYT (Presented at the EMP Phenomenology Review Meeting, AFWL, 3-4 May 73).

2. D. F. Higgins, C. L. Longmire, and A. A. O'Dell, MRC R-54 (Feb 73).

Capt Leon A. Wittwer
AFWL/DYT

1-2-3

# Satellite EMP from Buried Bursts

The buried burst is a previously unexplored geometry in which the upward directed gammas from an exospheric burst, in interacting with air of ever decreasing density, produce a strong propagated EM pulse with a large angular coverage. The threat calculations reported here are based on the AFWL CHEMP code[1], modified by the inclusion of a swarm treatment[2] of secondary and ionospheric electrons to replace the collision dominated conductivity which fails badly in the high altitude source and heating regions of the buried burst.

1. L.A. Wittwer "CHEMP: A Code for Self-Consistent Calculations of High Altitude EMP" AFWL/DYT (this symposium).

2. D.F. Higgins, C.L. Longmire, and A.A. O'Dell MRC R-54 (Feb 73).

# PRELIMINARY CALCULATIONS OF THE GAMMA INDUCED EMP FROM A BURST BURIED IN THE ATMOSPHERE

Chris W. Jones
The Dikewood Corporation

William E. Page
Air Force Weapons Laboratory

Preliminary results of the gamma induced EMP resulting from a burst buried in the atmosphere are presented. The air conductivity is treated using a swarm calculation and the compton currents are treated in a self-consistent manner. The fields code can be used to propagate the pulse outside the source region.

1-2-5

Michael A. Messier

Mission Research Corporation

# THE SATELLITE EMP ENVIRONMENT: PROPAGATION THEORY

To date the EMP environment at satellite altitudes has been calculated in an almost routine manner using linear propagation theory and several physical and mathematical approximations. These methods are reviewed and their validity discussed, relative to the larger problem of environment uncertainty and system vulnerability. Recent calculations which indicate the importance of considering non-linear effects are shown.

Abstract submitted for the Joint Electromagnetic
Pulse Technical Meeting at the Air Force Weapons Laboratory
Kirtland Air Force Base, New Mexico, 25-27 September 1973

## A MODEL OF THE EMP ENVIRONMENT SEEN BY A SATELLITE

A model of the EMP environment seen by a satellite, D. A. Dahlgren and C. N. Vittitoe of Sandia Laboratories, Albuquerque, New Mexico. An empirical model has been developed to estimate the worst-case external electromagnetic pulse incident upon a satellite. Facets of the model include estimates of the weapon asymmetry signal, the high-altitude radiated EMP, atmospheric refraction, reflection by the earth's surface, ionospheric dispersion, and variation due to weapon yield as well as due to orientation with respect to the earth's geomagnetic field. The model is used in a satellite vulnerability model that calculates probabilities of various weapon environments at the satellite, with given burst-position and given satellite orbit. The relation between the position of the satellite in its orbit and the timing of the burst at its given position can be taken to be random. Required integrations around the orbit demand rapid computer estimates of the EMP. The EMP model and some of the results are described.

1-2-7

# The Proposed Satellite EMP Environment Criteria

by

Lt William A. Seidler
Air Force Weapons Laboratory

Developments in the models of EMP generation have caused changes in the old criteria levels. The factors which went into the development of the proposed criteria and its impact on system environments will be discussed. Included for inspection but not part of the criterion are effects of nonlinear propagation in the D-region of the ionosphere and bursts located in the source region.

Joint Electromagnetic Pulse Technical Meeting
25-27 September 1973, Albuquerque, New Mexico
Abstract of Proposed Paper, (Chairman, Mr. John Darrah, AFWL (EL))

TITLE: Soviet Research in Nuclear EMP

CLASSIFICATION OF PAPER: Secret

CLASSIFICATION OF ABSTRACT: Unclassified

A qualitative analysis is presented of Soviet work in the following areas: the basic physics of EMP generation, air chemistry in a nuclear burst environment, coupling of EMP fields into systems and measurement of the time dependence of electric fields in the source region. Parallels are drawn between Soviet and U.S. EMP work and basic differences are discussed.

Myron W. Knapp

Lawrence Livermore Laboratory

# EMP Source Characteristics Experiment on an Underground Nuclear Event.*

Under sponsorship of the Advanced Research Project Agency, the Lawrence Livermore Laboratory conducted an EMP experiment as an add-on to an underground nuclear event. The experiment was the first, and only one, in a planned series of experiments, the purpose of which was to document the characteristics of EMP signals generated by various underground nuclear events in order to provide checks for theoretical models under development. A major program goal was to establish how specific event geometries affect the signals generated. For this first experiment, two separate EMP source mechanisms were considered: that due to an asymmetric gamma ray distribution resulting from shielding and geometry constraints in the vicinity of the device, and that due to currents induced on the line-of-sight pipe. The as-fired geometry differed significantly from the planned geometry; hence the instrumentation was not ideally located to sort out the two mechanisms. Nevertheless, signals characteristic of the two mechanisms seem to be apparent in the data. An impulsive (10 MHz) component of the signal is probably due to the asymmetric gamma distribution. A ringing component (1 MHz) has been attributed to currents on the LOS pipe.

*Work done under the auspices of the U.S. Atomic Energy Commission.

# TIME-DEPENDENT NEUTRON AND SECONDARY $\gamma$-RAY WEAPON OUTPUT INCLUDING COMPLETE COLLISION KINETICS *

T. A. Gabriel
Oak Ridge National Laboratory

A version of MORSE has been developed to incorporate the scattering effect of rapid radial expansion and of high temperature associated with the detonation of a nuclear device on the neutron and gamma-ray leakage spectra. The particular nuclear device considered in these calculations is of the Tamborine type, and the time-dependent system description was obtained from a VERA calculation performed by $S^3$. All of the neutron and gamma-ray transport calculations were accomplished using a modified version of the time-dependent Monte Carlo code MORSE.[1] The main changes made to MORSE were (1) modifications of the standard spherical geometry routines to accommodate a time-dependent geometry, (2) modifications of the cross section modules to account for the time-dependent density, and (3) the addition of transformation routines for handling the transformations to and from the rest system and the moving target nuclei at each collision. The coupled neutron and gamma-ray cross sections (75N-18G,P3) were obtained through the use of the code AMPX.[2,3]

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[1]E. A. Straker, et.al., "The MORSE Code - A Multigroup Neutron and Gamma-Ray Monte Carlo Transport Code," Oak Ridge National Laboratory Report ORNL-4585 (1970).

[2]N. M. Greene, et.al., "AMPX: A Modular Code System for Generating Coupled Multigroup Neutron-Gamma Libraries From ENDF/B," ORNL-TM-3706 (AMPX-1), To Be Published.

[3]The author wishes to thank Mr. John E. White of the Oak Ridge National Laboratory for the processing of the coupled neutron and gamma-ray cross sections.

*This work funded by Defense Nuclear Agency Program Under Subtask PE050.

1-2-11

# LATE-TIME ELECTRIC FIELD INTENSITIES FROM NUCLEAR BURSTS

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ABSTRACT

Two aspects of the electric field intensities induced at late times after detonations of surface and near-surface bursts have been studied recently under ONR sponsorship.

The first aspect concerns the production of lightning discharges that have been observed in a number of cases following nuclear bursts. From our analysis this phenomenon appears to result from a strong polar-angle field component which is generated, certainly at late times, by a ground burst.

The second aspect concerns the interpretation of data which have recently been released in the open literature [JGR 1972] and which describe strong static electric field intensities generated by rising nuclear debris clouds. These data have been reanalyzed and an interpretation of the source of the strong dipole electric moments of debris clouds will be proposed.

# A REVIEW OF EVALUATED CROSS SECTION DATA FOR AIR AND GROUND CONSTITUENTS

by

P. G. Young

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Los Alamos, New Mexico 87544

Abstract

During the past few years the Defense Nuclear Agency has sponsored a radiation transport program that has the goal of substantially reducing uncertainties in predictions of radiation environments. Important aspects of the program have been to provide new cross section measurements directed particularly at areas of ignorance in the data for several important materials and to maintain up-to-date cross section evaluations that fully incorporate the new experimental information. As a result, significant improvements have been made in recent years in the availability and accuracy of evaluated data for a number of materials, particularly in the area of gamma ray production.

In the present paper a review is given of the status of evaluated cross section data for common air and ground constituents including C, N, O, Al, Si, Ca and Fe. Particular emphasis is given to the air materials and to recent improvements in gamma ray production data. Comparisons of presently available evaluated data with the results of extensive new experimental measurements are given, and summaries of estimated errors in the evaluated data are presented. The increased accuracy of cross sections for other processes, such as neutron inelastic scattering and charged-particle production, that results from the improved gamma ray data is discussed. In addition, likely future trends in the evaluated data sets for air and ground constituents are outlined.

* Work supported by the Defense Nuclear Agency under Subtask PC102

ENVIRONMENT SECTION

Session 3

Wednesday Afternoon        26 September 1973

Chairman: W. T. Wyatt
Harry Diamond Laboratory

1-3-1

# EMP PEAK FIELD CALCULATIONS WITH THE HEMP/B CODE

BY

William E. Page
Air Force Weapons Laboratory

Calculations of early time high altitude EMP have been done using more detailed models for determining the conduction and Compton currents than those used in older HEMP calculations. The methods used in HEMP/B to account for Compton electron kinetics and ionization buildup are discussed. Recent calculations of EMP from Stockpile and from "Worst Case" sources are described.

1-3-2

William A. Radasky

Mission Research Corporation

THE HIGH-FREQUENCY EMP PRODUCED FROM HIGH-ALTITUDE BURSTS

Due to the increasing interest in the high-frequency (above 100 MHz) Electromagnetic Pulse (EMP), studies have been made employing recent CHAP code predictions of EMP. These predictions have been compared to the present high-altitude criterion, and significant differences are evident. This paper will present a study of the variation of the high-frequency EMP with such variables as weapon output, height of burst, weapon yield, and electron cascading.

1-3-3

## CHAP--Physics and Results

H. Jerry Longley and Conrad L. Longmire

Mission Research Corporation

The CHAP ("Compton High Altitude Pulse") computer code calculates the electromagnetic pulse (EMP) produced by the gamma rays from high altitude nuclear bursts. It is designed to be accurate in the first few microseconds of retarded time. Consequently only unscattered and once-scattered prompt gamma rays are considered. Compton recoil electrons are injected at frequent time steps, with weight proportional to the gamma flux and the air density, with the Klein-Nishina angular distribution. Their equations of motion are solved, taking into account the geomagnetic field and the EMP fields, and also their slowing down and multiple scattering by the air. The total Compton electron current is accumulated. The ionization produced by the Compton recoil electrons and by cascading due to the electric field (air "breakdown") is accumulated, and allowed to decay by attachment to $0_2$. The electrical conductivity is determined from the electron density and the electric field. With the Compton current and air conductivity so determined, Maxwell's equations are solved, first in the single ray approximation in which only radial and time derivatives are retained, and angular derivatives are dropped. An an option, after solving Maxwell's equations on three rays closely spaced in angle, the full Maxwell equations, including the angular derivatives, are resolved in a perturbation treatment to find the first order effect of the angular derivatives. As other options the user can: Use a delta function or a continuous function for the gamma pulse; either include or not include the EMP fields in the equations of motion of the Compton electrons. Many physical parameters and computational parameters can be chosen at will. Results from the CHAP EMP code will be given. Several specific calculations will be presented.

# 1-3-4

## LHAP-Physics and Results


H. Jerry Longley and Robert M. Hamilton

Mission Research Corporation


LHAP is a computer code for calculating the EMP produced by the prompt gammas from a high-altitude nuclear burst. It is based on the far plane approximation, which assumes that the earth is flat and also that the nuclear burst occurs above the atmosphere at an infinite distance away and has an infinite yield. These assumptinns imply that the resulting gamma ray front will be planar, and therefore the sources and the resulting fields will be functions only of the height along the gamma ray front and the retarded time. This approximation allows LHAP to be accurate to about 100 μsec of retarded time. The sources in LHAP must include both the first scatters of the gamma rays and at late times the multiple scatterings. The first scatters are calculated analytically in LHAP, since the number of mean free paths at any altitude is known. The subsequent (multiple) scatters are calculated in a Monte Carlo Code called LHAP-S. LHAP adds the currents and the ionization rate calculated in LHAP-S to the quantities it calculates due to the first scatters. The resulting total delta function currents and ionization rate are folded with the time history of the gamma ray output to obtain the sources for Maxwell's equation. The results from four LHAP problems and a comparison of LHAP and CHAP will be given. The four LHAP problems are identical except that they calculate the electromagnetic fields and sources (EMP) in four different directions from a nuclear burst.

# SENSITIVITY OF SELF-CONSISTENT CALCULATIONS OF HIGH ALTITUDE EMP TO TREATMENTS OF CASCADING, SCATTERING, AND PRECURSOR IONIZATION

Capt G. H. Canavan, Capt J. E. Brau, Capt L. A. Wittwer

Air Force Weapons Laboratory

The AFWL CHEMP code[1] for self-consistent calculations of high altitude EMP is used here to assess the energetic consequences of self-consistency, with particular attention to the alteration of the radiated electromagnetic pulse. Parametric studies indicate the sensitivity of the radiated fields to gamma spectrum, angular distribution of Compton electrons, scattering, cascading, and source region conductivity. The latter point is elaborated on through predictions of the reduction of radiated fields by small amounts of precursor ionization in the source region. System sensitivity to these alterations is briefly discussed.

1. L. A. Wittwer, J. E. Brau, G. H. Canavan, "CHEMP: A Self-Consistent High Altitude EMP Code", AFWL/DYT (presented at the EMP Phenomenology Review Meeting, AFWL, 3-4 May 73).

1-3-6

Michael A. Messier

Mission Research Corporation

# MAGNETOHYDRODYNAMIC EMP

It is known that magnetic field fluctuations, which can be measured over large areas, exist for times on the order of a hundred seconds after a high altitude burst. Even though a generally accepted theory for the generation and propagation of these disturbances has not been developed, it is possible to estimate their magnitude and general characteristics. From this information, the electric fields generated at the air-ground interface can also be estimated. These fields are of interest for two reasons: (1) they may pose a threat to long cable systems and (2) they provide information on the low frequency content of high altitude EMP. The purpose of this paper is to bring these problems to light and stimulate investigation into this relatively unexplored region of EMP phenomenology.

1-3-7

# An Estimate of High Altitude Neutron Induced EMP

by

Capt Gary R. Knutson
Air Force Weapons Laboratory

and

James Marks
Science Applications, Inc.

Curve fits of the EMP sources produced by scattered gamma rays and neutrons at sea level were scaled to a Sprint weapon burst altitude. The geomagnetic turning effect was included by dividing the total current into three components according to the angle between the radial direction and the direction of the geomagnetic field of the earth. The late-time scaled sources were added to a direct beam gamma source and the fields were calculated using the two-dimensional code HAPS. Results are presented for a Sprint yield of gamma rays and neutrons.

## 1-3-8

# Evaluation of High-Altitude EMP Data (U)

by

G. B. Carpenter, H. G. Heubach, and G. H. Price

Stanford Research Institute
Menlo Park, California

## ABSTRACT

(U) Electromagnetic pulse (EMP) data from the 1958 and 1962 high-altitude nuclear test series are examined and their compatability with theoretical models of the signal-generation process based upon the high-frequency approximation is assessed. A general description of the observed signal behavior in the low-frequency regime, for which this model becomes inaccurate, is also given.

1-3-9

# RESEARCH IN TWO-DIMENSIONAL CODE TECHNIQUES FOR CALCULATING THE EMP ENVIRONMENT DUE TO HIGH ALTITUDE BURSTS

W. T. Wyatt, Jr.
USA Harry Diamond Laboratories
Washington, D.C. 20438

Recent work is described dealing with the development of a two-dimensional (plus retarded time) approximation to the vector wave equation for the electric field, in the case of EMP generated by a high altitude nuclear burst. A finite difference method is used to solve four coupled partial differential equations, for charge density and electric field intensity, in a prolate spheroidal coordinate system. Due to the large number of terms in these second-order equations (about 100 terms), a software approach is used to generate a sparse matrix representation of the difference equations at each time step. The matrix is reduced to upper triangular form by a Gauss algorithm for band-structured matrices, to obtain the electric field and charge density at each time step.

1-3-10

# The Effect of Nuclear-Coulomb Electron Scattering on High Altitude EMP Sources

by

Capt Gary R. Knutson
Air Force Weapons Laboratory

and

Capt John Morgan
Air Force Weapons Laboratory

A Monte Carlo electron transport code was used to calculate the EMP sources produced by monoenergetic electrons, by a Compton scatter distribution of electrons, and by a photoelectric scatter distribution of electrons. The effects of nuclear-coulomb electron scattering, of the continuous slowing down method of electron energy loss, and of electron turning in the geomagnetic field of the earth were included in the calculations.

Analytic results were obtained from the source routines of two AFWL one-dimensional EMP codes. The older HEMP II routine includes an approximate method of electron slowing down and one average value electron in one direction. HEMP B sources include an improved slowing down model and the option of two electron scatter approximations based on small angle scatter theory; one based on an average obliquity of the distribution, and the other based on a random selection of scattering direction.

The Monte Carlo results are compared to the analytic source of HEMP II and HEMP B for a typical weapon gamma time history.

## 1-3-11

# CALCULATIONS OF LATE TIME GAMMA RAY INDUCED EMP

by

William E. Page
Air Force Weapons Laboratory

Arne A. Henden
The Dikewood Corporation

James A. Marks
Science Applications, Incorporated

EMP source calculations have been extended to late times (100 μsec) by means of γ-ray Monte Carlo calculations coupled with a Compton electron analysis. Preliminary field calculations based on one and two dimensional models have been compared. A description of the calculation and comments on the preliminary results will be given.

1-3-12

# HIGH ALTITUDE EMP

Dick Knight
Science Applications, Inc.

The high altitude EMP environment problem is discussed, with emphasis on the two-dimensional HAPS code. The physics including the assumptions and approximations used in both the source and field codes will be treated.

Results of calculations made with HAPS will be presented. A comparison will be shown on the HAPS calculations and results produced by the one-dimensional code, HEMP as well as the two-dimensional code B.

# A NUMERICAL EXAMPLE OF THE EFFECT OF ATMOSPHERIC SCATTERING ON PREDICTED EMP ENVIRONMENTS

C. M. Crain
The RAND Corporation

As outlined by Booker[1] the neglect of atmospheric scatter of Compton electrons causes the predicted amplitude of the pulse from a single detonation to be significantly overestimated with the over-estimation being related to the height in the atmosphere at which the Compton electrons are produced. For detonations which follow soon after an initial detonation scattering gives rise to still another pulse amplitude reduction factor. This factor is due to an increase in relative effectiveness of the secondary electrons created by the earlier detonation in absorbing the EMP signal produced by subsequent detonations because of an increase in height of the effective source. Both of these effects are illustrated numerically in this note.

1. Booker, H. G., "A Rough Outline of the Effect of Atmospheric scattering Below 50 Kilometers on Electromagnetic Radiation by Compton Electrons," Draft WN, The Rand Corporation, 1973.

ENVIRONMENT SECTION

Session 4

Thursday Morning 27 September 1973

Chairman: Richard R. Schaefer
R&D Associates

# CALCULATION OF THE EARLY-TIME X-RAY GENERATED EMP NEAR A HIGH-ALTITUDE SPARTAN WEAPON BURST

A. A. O'Dell, C. L. Longmire, and D. F. Higgins
Mission Research Corporation

The objective of this study was to estimate the x-ray generated EMP in the vicinity of a high altitude SPARTAN weapon burst. The calculations reported here are based on a self-consistent analytical technique described in an earlier report.[1]

The electric field is assumed to be primarily radial; thus the time rate of change of this radial field is directly proportional to the total current density. The effects of external fields and atmospheric anisotropy were neglected in the source current calculations. Therefore, only a local (non-propagating) radial electric field was generated in these calculations. The current density is divided into two parts. The primary current is produced by the high-energy photoelectrons created by the X-ray flux of the weapon. The secondary current is due to the low-energy ionization electrons. A swarm theory treatment relating the average electron energy, number density, and drift velocity is used to deal with these low-energy secondaries. The swarm theory treatment is somewhat unusual in that instant thermalization of the secondary electrons is not assumed. Instead, the temperature of the electron swarm is expressed as a function of time in a differential equation. As a net result five coupled differential equations are obtained which must be solved to find the radial electric field. The

1. D. R. Higgins, C. L. Longmire, and A. A. O'Dell, "A Method for Estimating the X-Ray Produced Electromagnetic Pulse Observed in the Source Region of a High-Altitude Burst," Mission Research Corporation Report MRC-R-54, Feb 1973 (Draft Report).

absolute magnitudes of the electric field and other key parameters are calculated at selected observer positions in the atmosphere and are presented graphically as functions of time for each observer position. These results are interpreted by the utilization of various approximate analytical procedures to verify the overall behavior of the calculated solutions and to provide check-points for selected limiting cases. Certain parameter sensitivity calculations were also included in this study.

# PREDICTIONS FOR PLATED WIRE MEMORY RESPONSE TO SGEMP

L. D. Singletary
TRW Systems Group
Redondo Beach, California

The purpose of this work was to perform a pre-test analysis specifically for the Northrop 2-mil plated wire memories to be placed in the Dido Queen underground test. However, the work was also directed, in addition to the above specific objective, toward (1) Identification of the chief mechanisms by means of which the information in the memory may be destroyed or its operation interfered with, (2) Determination of the influence of tunnels or gaps on the IEMP generated in the memory, (3) Determination of the failure levels expected for the Northrop memories. This information was to be used to modify the test design as regards the Northrop memories and also to extrapolate where possible to effect test design recommendations for the other memories under study in the underground test, and (4) Derivation, where possible, of some scaling laws for relating the results of Dido Queen to the actual threat environment. The work included definition of worst case conditions for the Dido Queen test, support of design and planning of test instrumentation, and identification of possible failure mechanisms. This required a review of the Dido Queen environment, documentation of memory subsystems to be studied, and the design of test cassettes.

This paper contains a description and documentation of the plated wire memories to be exposed to Dido Queen. The paper presents an analytical approach, and includes a review of the Dido Queen environment. It also discusses a number of computer codes at TRW which were used to calculate the photon transport, electron emission, electromagnetic fields and transmitted electron currents. The computer codes used included X-RAY, a photon transport code; PICS, a semiempirical electron transport code applicable to all media; SPACE, an electric field code; and SCAN, a code which calculates the electric field as a function of air pressure in the memory. The importance of the tunnels in the memory and the significance of whether they are vacuum or partially air filled is discussed. An inspection of the subsystem was made for significant coupling regions in worst-case orientation of the memory to the nuclear radiation.

A comparison of all the possible mechanisms for energy coupling into the memory was made. The current flow produced in the sense wires and word straps due to the coupling of generated electromagnetic fields into the wires by either inductive coupling or by direct field effects on the magnetic domains of the plating was considered as well as the effect of photon irradiation produced by direct charge or electron transfer.

The paper will present the conclusions which state that the replacement currents generated in the memory appear to be the dominant mechanism for "bit disturbance". Next in importance is the effect of the generated magnetic fields on the magnetic domains. Finally, the inductively coupled magnetic fields must be considered. The latter mechanism may be more important for a side illumination of the memory. However, then the replacement current effect would in general be reduced and the fields would be smaller at the edges of the memory due to the smaller exposed area.

# TWO-DIMENSIONAL, TIME-DEPENDENT COMPUTER CALCULATIONS OF CURRENTS AND FIELDS IN A CYLINDRICAL CAVITY FOR IEMP CONDITIONS*

E.P. Wenaas, E.P. dePlomb, and A.J. Woods
INTELCOM RAD TECH

An evacuated cylinder with conducting walls is irradiated from the end by an axially symmetric photon source. Photo electrons emitted from the surfaces to the inside of the cylinder produce electric and magnetic fields which in turn act on the electrons. Electric and magnetic fields, potentials, and currents are calculated within the cylinder as a function of time. These quantities are obtained by utilizing the 2-D, time dependent IEMP computer program, TEDIEM-RZ.

The TEDIEM-RZ code calculates this problem using emitted electron spectra and angle distributions obtained from standard emission codes. The emission electron space, energy, angle, and time distributions are inputs to the code. The Green's function technique is employed for the electric fields, and the particles are moved by appropriate force equations. A summary of calculations performed using TEDIEM-RZ will be given which includes effects of geometry, current level, and electron spectrum on fields and currents within the cylinder. Also, a more detailed analysis of results of back emission and reflection of electrons from cavity walls will be presented.

Simplified IEMP calculations are generally done using emission of electrons in the forward direction only. Also, electrons are usually assumed to "stick" to the cavity walls when they hit them. Studies have been conducted in which electrons were emitted in the backward direction and also allowed to be reflected from the cavity walls. The results show that these effects can be important under certain conditions of interest in IEMP. Results of the studies will be presented.

*This work was sponsored by the Defense Nuclear Agency under Contract DNA001-72-C0090.

# TWO DIMENSIONAL, TIME DEPENDENT COMPUTER CALCULATIONS FOR SGEMP ABOUT A CONDUCTING SPHERE*

E. dePlomb, E.P. Wenaas, and A. Woods
INTELCOM RAD TECH

The new SGEMP code, TEDIEMS, calculates electromagnetic fields, surface currents, return and escape currents due to photoemission and backscattering from a conducting sphere in vacuum.

Emission current levels and energy distributions are obtained from existing emission codes. Particles of charge are used to represent the emission, return, and escape currents. A quasi-static Green's Function method is used to calculate the electric fields at each time step. A relativistic equation of motion for the kinetics is used.

Results from a large number of realistic sample problems are summarized. The limitations and advantages of the quasi-static approach are discussed and useful generalizations are presented for the range of problems in which this code is applicable.

*This work was sponsored by the Defense Nuclear Agency under Contract DNA001-72-C0090.

1-4-5

# COMPUTER SOLUTIONS OF IEMP PRESSURE EFFECTS, INCLUDING SPATIAL, TEMPORAL, AND ENERGY DEPENDENT PROCESSES*

E.P. Wenaas, E.P. dePlomb, T.N. Delmer, and A.J. Woods
INTELCOM RAD TECH

The computer code, SPARKP, is utilized to calculate pressure effects upon current transmission and electric field dissipation in a one-dimensional parallel plate geometry. Spatial distributions and energy dependent cross sections are computed in detail at each time step. Calculational techniques include combining a "particle" calculation for primary electron motion and a "continuum" model for the background plasma. Primary electrons are emitted from the cavity walls by photo-emission, and secondary electrons are produced in the gas by collisional ionization.

Calculations are presented which show the effect on fields and transmitted currents due to gas pressure, emission current level, and plate spacing. These results are summarized and shown to compare favorably with experimental work at two different simulation facilities.

*This work was sponsored by the Defense Nuclear Agency under Contract DNA001-72-C-0090.

ABSTRACT

# CLOSE-IN RADIAL ELECTRIC FIELD PULSES

Stanley Schneider
Nuclear Vulnerability and Hardening
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A simple analytic treatment of the close-in radial electric field produced by x- and gamma ray pulses at various altitudes and separations from the bursts is made. The calculation treats the time varying electric susceptibility and conductivity induced in the air by the radiation for levels of contemporary interest. The strong field back reaction on the photoelectric and Compton electrons are discussed and treated for fluence parameters of interest.

Two types of analyses are done: (1) time dependent treatment of the Sommerfeld formula for the electric field produced by relativistic particles generalized to the ionized medium, and (2) saturation fields calculated from the time dependent induced electric susceptibility and conductivity and the emitted electron currents corrected for the back field reaction on the electron motion.

This paper is recommended for presentation in technical area a (Environment) and will be classified Secret Restricted Data.

Orlando Lopez

Kaman Sciences Corporation

# PHOTOCURRENTS AND SELF CONSISTENT FIELDS IN CAVITIES - AIR PRESSURE EFFECTS

When a pulse of photons impinges upon a cavity, electrons are emitted from the cavity walls. If the electron transit time is of the same order as the characteristic time of the fields and the potential induced inside the cavity is of the same order as the energy of the electrons, the resulting problem has to be solved self consistently. If, in addition to these complications, the cavity is not fully evacuated, the effect of secondary electrons has to be considered. Secondary electron currents can neutralize the space charge fields, thereby increasing the transmitted current and causing higher magnetic fields inside the cavity.

In this paper, we present a method to effect a dynamic self-consistent solution to the problem. This is achieved by an application of the particle-in-cell (PIC) method used for plasma simulation(1). By following the time evolution of the potential and the electric field (and monitoring the position and magnitude of the potential minimum) in a one dimensional cylindrical calculation, a clear physical picture of the physics of space charge neutralization is obtained. Results for a fully electromagnetic, three dimensional calculation will also be presented and compared to underground test data.

(1) R. L. Morse in Methods of Computational Phys., Vol. 9, Academic Press, N.Y., N.Y., 1970.

John P. Roberts, Harry Diamond Laboratories
Thomas M. Jordan, Experimental and Mathematical Physics Consultants, Inc.

# The Effects of Coherent Scattering and Polarization on Photon Fluence and Absorbed Dose in Three Model Geometries

The study at Harry Diamond Laboratories of photon transport and absorption at deep penetration distances and their effects on Compton source currents and ionization rates has resulted in an examination of two basic photon interactions usually not considered significant; namely, coherent scattering and polarization of photons. Significant changes in fluence and absorbed dose were noted when selected calculations including and omitting these effects were compared.

Using the FASTER III Monte Carlo radiation transport code, correlated calculations for a 1-MeV photon point source were made for an infinite air geometry containing an aluminum sphere with a point detector at its center. The distance from source to detector was 1 km in air with a density equivalent to an altitude of 50 km. Calculations were made for three model geometries in which the radius of the sphere was varied to be 25 cm, 50 cm, and 100 cm. For each geometry three sets of data were obtained. These were: a calculation set that did not include coherent scattering and polarization effects, a second set that included form factors for coherent and incoherent scattering, and a third set that included not only the form factors for coherent and incoherent scattering but also accounted for the effects of polarization of multiply scattered photons from an unpolarized source.

The most significant differences due to consideration of these effects were noted for the model geometry containing the 100-cm radius aluminum sphere. Comparison of the results for this geometry for the three sets calculated showed that the largest differences existed between the first set, which did not include coherent scattering or polarization, and the third set, which included both. The value in the third set of the photon number fluence at the point detector in the center of the aluminum sphere was 23 percent lower than the number fluence value in the first set. Also the energy fluence at the detector for the third set was 10 percent less than the energy fluence result calculated for the first set. Finally, for an aluminum absorbed dose response the dose at the point detector for the third set was 17 percent less than the dose for the first set. From the differences shown above we conclude that consideration of coherent scattering and polarization effects in determining fluence and dose is necessary.

# RADIAL EMP CALCULATIONS

Philip J. Hart
Lockheed Missiles and Space Company, Inc., Sunnyvale, California

A self-consistent method is used for calculating the time variation of the radial EMP field and of the air conductivity in the vicinity of a nuclear burst. The fundamental integro-differential equation is derived and solved numerically. In general, the approximations used, such as neglect of the geomagnetic field, are such as to yield an upper limit to the actual radial E field. However, the important influence of the instantaneous electric field in reducing the range of the Compton electrons and thus of the resultant primary charge separation is included in the calculations, as well as the field-dependent attachment and avalanching rates. The gamma ray spectrum is resolved into a finite number of energy intervals (currently 10), and the attenuation within each interval is calculated along the slant range between burst and observer for any angle of elevation. By using algebraic equations to closely approximate the variations of many parameters (air density, gamma pulse shape, gamma mean free path, attachment and avalanching rates) over appropriate intervals of their independent variables (altitude, time, energy, field), it becomes possible to obtain prompt solutions with an electronic calculator such as the HP 9800A with extended range. Example curves showing electric field and air conductivity versus time will be presented. The rapid increase of conductivity with avalanching is particularly effective in limiting the peak field attained. For high yields and close distances, the electric field decays much more rapidly than the conductivity, but for low yields and/or greater distances the converse may be true, having a rather small residual field which decays very slowly.

1-4-10

# ELECTROMAGNETIC FIELD OF CHARGED PARTICLES EMITTED FROM THE EXTERNAL SURFACE OF A CONDUCTOR

Kelvin Lee
Dikewood Corporation, Westwood Research Branch
Los Angeles, California

In calculating the external system-generated EMP of photoelectrons emitted from the surface of a conductor it is convenient, from both the mathematical and physical viewpoint, to first split the field into its irrotational and solenoidal part. For non-relativistic electrons the irrotational part of the field can be obtained with sufficient accuracy by solving an appropriate quasi-electrostatic problem and the solenoidal part by solving an appropriate quasi-magnetostatic problem. A validity criterion on the quasi-static solutions can be established by solving a canonical problem rigorously as well as approximately. The canonical problem involves an electron orbiting a perfectly conducting sphere. The rigorous solutions for the induced surface currents and charges on the sphere are compared numerically with the quasi-static solutions, thus establishing validity criteria in terms of the electron's kinetic energy and distance from the sphere. These quasi-static solutions can be generalized to arbitrary motions while the rigorous solutions cannot. For arbitrary-shaped conductors the integral-equation approach can be employed for the two quasi-static problems. The investigation has so far been limited to the calculation of the induced surface currents and charges on a perfect conductor with the trajectories of all electrons specified.

1-4-11

# Spherically Symmetric IEMP Charge and Field Distributions

Donn G. Shankland

Air Force Institute of Technology
Wright-Patterson AFB, Ohio

## Abstract

The charge and field distributions for inwardly emitted electrons in a spherical geometry are obtained by solving the Vlasov equation by the method of characteristics for arbitrary (smooth) energy spectra. Asymptotic forms are derived for Maxwellian distributions, and time-dependence is discussed. As the total current increases, a sheath is observed to form just inside the shell, partially screening the interior.

1-4-12

# X-RAY INDUCED CURRENTS ON A METALLIC SPHERE

R. Stettner and D. F. Higgins
Mission Research Corporation

A numerical solution of the time dependent Maxwell's equations is described for low energy x-rays incident on a metallic sphere. The solution is non-selfconsistent, assuming that the photoelectric current source is unaffected by the electric fields it produces. The variation of the currents and charge on the sphere and currents leaving the sphere are described in intervals of time which are a fraction of the time required for light to cross the sphere. The error made in calculating the surface currents by neglecting the finiteness of the velocity of light is also discussed. Results are presented for time varying low energy x-ray flux densities, with a black body energy spectrum, impinging on a metallic sphere.

INSTRUMENTATION SECTION

INSTRUMENTATION SECTION

Session 1A

Wednesday Morning 26 September 1973

Chairman: Keith Treece
Sandia Corp.

2-1A-1

# A SURVEY OF THE STATE-OF-THE-ART OF FAST SINGLE TRANSIENT ANALOG TO DIGITAL CONVERTER TECHNIQUES

Ralph E. Partridge
Los Alamos Scientific Laboratory

Analog to digital converters and associated memories are being used with increasing frequency for fast single transient waveform recording where application of the conventional oscilloscope and camera approach is not feasible. This paper reviews the recording processes in fundamental terms, surveys recent developments in techniques, and discusses potentially applicable new technologies.

ABSTRACT

## 2-1A-2

## EVALUATION OF AN ANALOG-TO-DIGITAL RECORDING SYSTEM FOR USE IN EMP DATA ACQUISITION

R. R. Creason and J. C. Wirth

Braddock, Dunn and McDonald, Inc.

An evaluation program is currently being implemented at the ARES facility during which the performance of an AFWL-procured analog-to-digital pulse recording system (Tektronix 7912) will be evaluated. The evaluation will consist of three phases. During the first phase, the performance of the basic A-D system will be evaluated to determine resolution, accuracy, noise susceptibility, writing characteristics, etc. During the second phase, the A-D system will be tied into a NOVA 1200 computer to assess interface compatibility and to develop acquisition and processing software. During the third phase, the A-D system will be used with the NOVA in an operational configuration. This configuration consists of the A-D system located in the ARES screen room, the NOVA 1200 located in the ARES data trailer and a long interconnecting data cable. The objective of this third phase is to define and correct deficiencies in an operational configuration with a real EMP environment.

This paper will report the results of the above efforts and will provide recommendations for integration and use of A-D recording systems in EMP data acquisition systems.

2-1A-3

# SINGLE TRANSIENT ANALOG TO DIGITAL CONVERSION SYSTEM

John D. Parks, US Army, Harry Diamond Laboratories

Abstract:

Analysis of complex single transient waveforms may be simplified by converting the amplitude vs time trace of the function into digital format for analysis by computer programs. A system for converting an oscilloscope single sweep, the photograph of an oscilloscope trace or the plot of a single valued function to digital format is described. The applications and advantages of using this system in the analysis of test data from EMP tests are outlined.

by Dr William R. Graham, RDA
and Chris Ashley, AFWL.

Abstract

Estimation of Errors in Calculating Transfer Functions from Pulse Data

Analysis of responses of linear systems, or of linear subsystems within larger systems, to transient stimuli commonly involves the concept of transfer functions. Estimation, verification, and use of these transfer functions often entails measurement of transient stimuli and transient system response. These data are then digitized and processed numerically to produce the transfer function. The measurement and digitization processes are usually the most important sources of error in the transfer function measurement. Conclusions drawn about the systems being analyzed are correspondingly in error. The purpose of this paper is to discuss some ways of estimating the magnitudes of the important errors in the data reduction process and to show how errors in the transfer function are related to errors in that process.

2-1A-5

Jiunn S. Yu, Boyd D. Boitnott and Robert L. Hutchins
Braddock, Dunn and McDonald, Inc./ARES

# STATISTICALLY IMPROVED SPECTRUM PAST 100 MHz OF EMP ENVIRONMENTAL DATA AND STATISTICAL ANALYSES IN THE TIME DOMAIN

The EMP at ARES are monitored by sensors placed near the working volume. The sensors' outputs are displayed on oscilloscopes after passive integrators. Pictures are then taken of the scopes' traces for permanent records and for digitizations to quantify EMP characteristics in both time- and frequency-domains. This paper is concerned with fundamental statistical procedures through which desired informations are estimated with associated standard deviations.

Simultaneously recorded traces of fast- ans slow-sweeps are consistently digitized n times. Their arithemetic means are estimated as functions of time, and the associated standard deviations are shown to increase in proportion with the trace's rates of change. Fourier transforms are performed for each of the n digitized traces to obtain complex arithemetic means for spectral densities. Associated standard deviations in frequency-domains are plotted to show their variations with the spectral densities. Results from using slow-sweeps alone are shown to have lower-confidence estimates in the higher frequency region. Relatively high-confidence spectral densities are obtained for frequencies as high as 115 MHz for ARES EMP when proper time-tyings are performed for fast- and slow-sweeps.

The techniques presented here are straightforward and useful. Although they are not studied for reducing systematic errors that might result from improper processing, they are shown to have effectively reduced random errors and improved earlier techniques employed at ARES.

D R . D A V I D L E E

*and*

1 / L T D A V I D A U D L E Y

*will speak on*

# A N A L T E R N A T E S Y S T E M R E P R E S E N T A T I O N F O R A N A L Y Z I N G E M P D A T A W I T H E R R O R B O U N D S

ABSTRACT: AN ALTERNATIVE TO SYSTEM REPPESENTATION BY IMPULSE RESPONSE (OR TRANSFER FUNCTION) IS INTRODUCED. AN ADVANTAGE OF THE NEW REPRESENTATION IS A COMPUTABLE ERROR ESTIMATE ON SYSTEM RESPONSE. NUMERICAL METHODS BASED ON THIS REPRESENTATION ARE APPLIED TO "GREEN BOX" DATA AND TO MM IN-PLACE DATA.

INSTRUMENTATION SECTION

Session 1B

Wednesday Morning 26 September 1973

Chairman: Ralph Partridge
Los Alamos Scientific Laboratory

# MUTUAL INDUCTANCE CURRENT PROBE DEVELOPMENT

W. Reed Edgel
Albuquerque Division, EG&G, Inc.

## ABSTRACT

This paper describes Mutual Inductance Current Probes (I-dot Sensors) developed for the Air Force Weapons Laboratory. The probes are annular ring-shaped devices, with aperture diameters ranging from 0.1 to 2 meters. The sensor's output is proportional to the first-time derivative of the total current through the aperture. The theory of operation, design, and construction of the sensors are discussed.

Developmental testing of these sensors yielded data concerning step function response, sensitivity dependence on off-axis current position, sensitivity verification, and time domain reflections. These tests and test results are discussed.

Current probe applications and guidelines are presented, along with descriptions of new types of current probes under development.

2-1B-2

# AN ELECTRO-OPTIC EMP E-FIELD SENSOR

Glen J. Morris

Albuquerque Division, EG&G, Inc.

## ABSTRACT

An electro-optical modulator, consisting of a Pockels cell and an analyzer, is an excellent transducer for measuring electric fields. Such a system, which possesses good sensitivity and extremely wide bandwidth, can be made. The Pockels-cell sensor is based on the Pockels effect, in which the presence of an electric field causes induced birefringence in a suitable crystal. With the addition of a quarter-wave-plate analyzer, it is possible to modulate the irradiance of a laser beam passing through the crystal in accordance with the electric field applied to the crystal. In usual applications, the electric field within a Pockels-cell modulator is produced by a potential difference applied to a pair of electrodes attached to the crystal. In the EMP application, the electric field is produced by a simulator. A Pockels-cell modulator located within the EMP field will respond to that field. There is no need for any connections to the crystal. The crystals used are dielectric in nature, and cause minimum field perturbations. A three-axis sensor, capable of measuring both field strength and direction, is feasible.

# SOURCE LOOP CALCULATIONS FOR B-DOT SENSOR

James L. Harrison
Albuquerque Division, EG&G, Inc.

## ABSTRACT

An "electrically-small" B-dot sensor, having an equivalent area ($A_{eq}$) of 10 square meters, has been developed for the Air Force Weapons Laboratory. The sensor is a 50-turn loop, employing several advanced grounding and shielding techniques to enhance the high-frequency performance.

This sensor has been designed to permit its operation as a self-integrating sensor. In this mode of operation, the sensor's H-field sensitivity is related to an equivalent length ($\ell_{eq}$), which can be adjusted to a convenient number without changing the equivalent area.

# CHARACTERISTICS OF THE DRI SPHERICAL E-FIELD SENSOR

Mike Shields
Denver Research Institute
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Denver, Colorado 80210

A requirement for an electric field sensor capable of mapping transient electromagnetic fields in the kilovolt per meter range led to the development of an instrument package contained within a 25 inch diameter spherical shell. A radially mounted stub antenna serves as the electric field sensor.

The theoretical open circuit response for an incident plane wave is obtained by reciprocity for linear and sinusoidal antenna current distributions. The response as a function of the angle of incidence and as a function of the ratio of probe length to sphere diameter are presented and discussed.

# A Multiple Purpose, Low Reactance EM Field Sensor

BY U. Cocca, R.C. Fries, and L.C. Humphrey
General Electric Company, Syracuse, New York

The following outline is for your review and consideration for presentation at the Joint EMP Technical Meeting 25-27 September 1973. This outline should not be released for public use until approval is received from General Electric Company.

OUTLINE:

I. An EMP instrumentation technique for characterizing a parallel plate transmission line EMP simulator.

   1. Separately Measures E and B fields
   2. Measures their algebraic sum as it depends on the direction of propagation.

II. Novel (Directional coupler) sensor design

   1. Versatility in operation
   2. True derivative response to less than 1 dB over
   3. Six octave frequency range

2-1B-6

# OMNI-DIRECTIONAL B-DOT SENSOR DEVELOPMENT

W. Reed Edgel
Albuquerque Division, EG&G, Inc.

## ABSTRACT

This paper describes an omni-direction B-field sensor developed for the Air Force Weapons Laboratory. The sensor consists of three, mutually-perpendicular B-dot loops. It produces an output in response to a changing B-field in any direction. The sensor is used primarily for a trigger for EMP data acquisition systems, although it is also possible to use it for quantitative measurements of the magnitude and direction of the B-field. The paper discusses the theory of operation, design, and construction of the sensor; and it discusses prototype testing and test results. Applications and guidelines are also presented.

INSTRUMENTATION SECTION

Session 2

Thursday Afternoon 27 September 1973

Chairman: Mr. Don Forrester
EG&G, Inc.

# TRANSFER IMPEDANCE ACROSS INTERFACES CONTAINING CONDUCTIVE GASKETS*

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Abstract - Section e. Unclassified

Conductive gaskets are often used as a means of electrically bonding together metallic parts which form the outer conductor or shield of a system. A test method and procedure was developed to permit comparative evaluation of gaskets alike in shape but differing in conducting material present in the elastomer. The test method permits measurement of a directly meaningful quantity; namely, the transfer impedance added to that of a coaxial system by the gasket, using the same type of surfaces interfacing the gasket as in the proposed application.

A unique test fixture will be described; basically, two coaxial cavities coupled by the gasketed interface under test. A description of measurement methods includes verification testing with d-c instrumentation, to supplement measurements of transfer impedance up to 50 MHz. Measurement capabilities in the tens of microhms region can be achieved provided precautions, to be described, are taken to ensure coupling is exclusively by the interface under test.

Some test results will be presented, which can be explained in terms of the nature of the conducting materials in the gaskets, such as distributed particles, wire mesh, and expanded metal.

* This work was performed under Contract F04701-69-C-0198.

F. N. Holmquist
TRW Systems Group
Redondo Beach, California

2-2-2

# Measurement of Complex Conductivity of the Ground at Low Frequencies at Various Depths

The penetration of EMP signals into the ground and the propagation of signals on buried conductors are determined to a large extent by the ground conductivity and dielectric constant. These parameters vary from site to site, with frequency, depth and climatic conditions. At present, these parameters - expressed here in terms of the complex conductivity - are not adequately known. A method is proposed for in situ, low frequency measurements of the real and imaginary components of the ground conductivity by means of a small conductivity probe developed for probing tenuous plasmas.[1] In this application the probe is lowered to depth inside a plastic pipe driven into a similar diameter hole in the ground. The probe consists of three equally spaced, coil-wound, coaxial, ferrite toroids. Solenoidal electric field lines produced by oscillating magnetic flux in the two outer driving toroids thread through the three toroids and thence around through the plastic pipe and the surrounding ground material. When the probe axis is horizontal, i.e. perpendicular to the pipe axis, the conducting and polarizable ground results in an oscillating charge distribution in the ground regions just outside the ends of the probe. In effect, the probe acts like a transformer. The ground current, together with that portion of the displacement current which threads through the central toroid, serves as a single primary turn on the central detecting toroid. The amplitude and phase of the voltage on the coil of this toroid determine the complex conductivity of the ground. The effect of the pipe must be taken into account. Satisfactory probe operation depends on obtaining a suitably small or null signal when the ground is not in close proximity. This is accomplished by cancelling out the ever present voltages from unwanted coupling before lowering the probe or, more probably, when the probe is at depth and rotated 90° so that its axis is parallel to the pipe axis. The microvolt signals are measured with a phase sensitive lock-in voltmeter. Predicted capabilities and limitations of the probe will be discussed.

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[1]"A Conductivity Probe for Tenuous Plasmas," Fred N. Holmquist, AIAA Journal, Vol. 7, No. 2, February 1969, pages 205-210.

# THE SMART TEST SYSTEM

by

G. S. Parks, Jr.
Stanford Research Institute
Menlo Park, California

The term "smart" has been applied to this proposed frequency-domain test system because the use of a minicomputer as the system controller makes possible a system which can make decisions while performing a test. An inherent additional advantage is that the same minicomputer can carry out data processing, providing, within minutes, finished results which usually are not available until much after the tests are completed.

The elements of the system, nearly all of which are commercially available, are described and performance specifications are discussed. The specific types of decisions to be included in the software are examined on the basis of data quality and confidence.

# MEASUREMENT OF INSTRUMENTATION CABLE SHIELDING

M. K. Bumgardner
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ABSTRACT

It is very often necessary to install instrumentation cabling/current probes for the testing of EMP, EMR, or RFI induced currents on/or within a test vehicle in such a manner that they are inaccessible during testing. As a result, the current probe cannot be removed from the wire or cable to determine the induced noise present in the original measurement setup. A technique normally used to determine the order of magnitude of induced noise is that of installing a "dummy" current probe. If all of the cables and connectors in the inaccessible region have the same shielding integrity as the "dummy" probe, then the measurement obtained on the dummy probe and its cable is representative of the noise on all of the current probes and their respective cables.

This paper describes a technique to ensure that all of the instrumentation cables have a shield integrity within ±6 dB of the "dummy" probe's cable. The basic principle of this technique is a transmission line that is formed between the outer shield of the cable to be tested and an insulated wire that is spiraled along the cable. This transmission line is terminated in its characteristic impedance (usually 150 ohms) and provides a uniform axial current distribution, $I_{SH}$, along the cable shield, which is measured by a current probe. The voltage on the test cable's center conductor, $V_o$, is measured in a 50-ohm termination at the recording end of the cable, and can be used to determine shield effectiveness.

2-2-5


ABSTRACT

## NANOSECOND TIMING IN AN EMP ENVIRONMENT

A number of high speed Time Delay Generators, Fanouts, Time Interval Meters, Trigger and Marker Generators, etc, are discussed with emphasis on those characteristics that are unique to EMP applications. High speed optical inputs and outputs in addition to electrical inputs and outputs allow light pulse triggering thus eliminating RFI pickup on coaxial cables. EMP enclosures with self contained batteries enable operation in 200 KV/Meter fields. The design of the units is conservative to ensure reliable operation in actual field conditionsand over operating temperatures from 0 to plus 135 degrees F. The stability and accuracy of the units vary from ± .05 nanoseconds to ± 3 nanoseconds depending on range, extremes of temperature, etc.



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2-2-6

# PICOSECOND INSTRUMENTATION FOR A 100:1 ELECTROMAGNETIC SCALE MODEL OF EXOATMOSPHERIC EMP

Joseph A. Kreck, US Army, Harry Diamond Laboratories

Abstract:

Time domain measurements on a scale model range become extremely difficult when the pulse risetime of responses is on the order of 100 picoseconds. A successful effort to use a sampled data approach (equivalent time domain) has resulted in some interesting developments in pulse generating and sensing instrumentation.

This paper discusses generating a 70 picosecond risetime pulse by means of an impedance match reed relay and the subsequent radiation of this pulse with maximum fidelity. Current probes, a balun, and field sensors were developed to receive this fast signal. A discussion of delay lines used in the sequential sampling technique shows that "fastest is not always best." Finally, some results from a scale model simulation using this instrumentation will be presented.

# ACTIVE INTEGRATOR

R. M. Brown and J. L. Wells

BRADDOCK, DUNN AND MCDONALD, INC.
ALBUQUERQUE, NEW MEXICO

## ABSTRACT

The BDM Model BRC-25A Active Integrator is a wideband, solid state amplifier employing a passive RC network and an active amplification network. The instrument was designed and developed for the specific purpose of improving the quality of EMP data by providing gain and impedance matching.

Compared to the other integrators, the BRC-25A Integrator offers considerably less signal attenuation and does not require operation into a high impedance level. Since the Active Integrator uses an isolation amplifier stage, there are no changes in the RC integration time constant due to external output connections. The BRC-25A features a 25 micro-second time constant and an amplification of 35 dB. It is compact, port-able and self-powered, and employs a rechargeable, voltage regulated internal supply and active solid state components. It also features an externally actuated, internal calibration circuit. Since the integrator package is double-shielded, no protective enclosure is necessary for proper operation in open EMP environments.

The active integrator is a unique instrument, providing nanosecond integration of the time derivative field and current signals from sensor measurements in EMP research environments. The device is particularly useful in applications where a low voltage pulser is providing the EMP or where the nonprincipal field components of an EMP are being measured. With the use of appropriate attenuators, signal levels up to values in the kilovolt range can be integrated by the BRC-25A.

# OPTOELECTRONIC AND PNEUMATIC ISOLATION TECHNIQUES

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This paper describes a variety of techniques which have been successfully employed on the Minuteman EMP Test Programs for isolation of test instrumentation from the networks under test and from the test environment. These techniques have been applied to both CW and pulse instrumentation systems.

Transfer functions of large distributed networks must be measured where the network input and output ports are separated by distances which make accurate measurements difficult by conventional techniques. Measurements extend over very wide bandwidths and over very large dynamic ranges. Enormous errors can be incurred unless great care is taken to avoid ground loops and inadvertent modification of the network by the presence of instrumentation signal and power leads.

These problems have been eliminated through the use of proper instrumentation shielding, optoelectronic coupling of all instrumentation signal paths and through the use of compressed air as the prime power source for all critical instrumentation.

A wideband optical data link is described that provides for differential mode, phase-equalized transmission of 5 nanosecond risetime pulse data. Dynamic range is 34 dB. A forerunner of this equipment, used for stepped CW testing at discrete frequencies from 10 kHz to 100 MHz provided a dynamic range greater than 125 dB. Also described are narrowband (3 kHz) optical links that use audio or logic modules to transmit voice, control signals or digital data over 250 feet. Transmitter and receiver assemblies are powered by small air-driven alternator modules. Other special purpose signal and power isolation devices are also discussed.

This work was partly funded under Air Force Contract F04701-72-C-0210D.

2-2-9

# A 250-MHz MICROWAVE SYSTEM

Donald L. Trone
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## ABSTRACT

A 250-MHz bandwidth microwave telemetry system utilizing dielectric waveguide (DWG) was developed. Performance specifications include a dynamic range in a 100-Hz bandwidth of 88 dB, bandwidth of 250 MHz, and a dielectric waveguide range of up to 100 feet. The design is based on previous microwave systems designed and fabricated for EMP data acquisition. Primary alterations in design are; the elimination of a TWT, detector biasing to achieve linearity, critical matching and tuning of a balanced modulator, and the use of wideband video amplifiers. Temperature stability measurements on the input-to-output transfer function of the system were made using 80 feet of dielectric waveguide.

ABSTRACT

2-2-10

# 500 MHz TRANSIENT DATA TRANSMISSION SYSTEM

R. R. Creason and J. C. Wirth

Braddock, Dunn and McDonald, Inc.

The measurement of transient response data in an EMP environment requires transmission of the data to a remote isolated area for recording and processing. The bandwidth of the transmission of data over distances up to 150 feet with a video bandwidth of 10 KHz to 500 MHz.

The system consists of a portable double shielded battery powered transmitter of approximately 1 $ft^3$ volume. The transmitter consists of a video attenuator, coaxial switch, calibration generator, modulator, Gunn oscillator and waveguide output flange. The unit includes voltage regulators and pneumatically operated switches for power and calibration control. The video input is 50 ohm coaxial. Transmission of the data to the receiver is by dielectric waveguide.

The receiver used with this system consists of a waveguide input, attenuator, tunnel diode detector, microstrip switch, video amplifier and associated power supplies and microstrip switch drivers. The receiver includes an RF level meter which may be switched in to monitor and set the RF input to the detector for optimum linearity. The input attenuator also permits adjustment of detector input level to compensate for various waveguide lengths. Longer waveguide runs can be used with some loss in signal to noise ratio. Optimum power input to the detector is approximately -5dBm. The output impedance is 50 ohms and maximum video output level is approximately 5 dBm.

2-2-11

# A CIRCULAR FLUSH PLATE DIPOLE D-DOT SENSOR

by

Thomas O. Summers

EG&G, Inc.

The expected characteristics of a circular flush plate Dipole are described in SSN 98 and SSN 106. This sensor is a circular plate coplanar with a conducting plane, but isolated from it by a narrow slot. Under Air Force contract, sensors have been built and tested. This paper compares expected performance with laboratory measurement. Performance degradation associated with practical design constraints are described along with empirical solution to some of the problems.

INTERACTION SECTION

INTERACTION SECTION

Session 1A

Tuesday Afternoon 25 September 1973

Chairman: R. Mittra
University of Illinois

# DIFFRACTION OF AN ELECTROMAGNETIC PLANE WAVE THROUGH A NARROW RECTANGULAR APERTURE

By

M. R. Wilson

Abstract

Numerical results are presented for the Suzuki[1] approximate solution to a problem of plane wave diffraction through a narrow rectangular aperture. By assuming the width of the slot to be small, Suzuki obtains an analytic expression for the aperture electric field. We calculate the frequency domain fields behind the slot by Gaussion numerical integration over the aperture. The latter results are compared with an analytic dipole approximation to the diffracted fields. Finally, we obtain through numerical transform techniques, the time domain diffracted fields in response to an incoming transient plane wave.

[1] Suzuki, M., "Diffraction of Plane Electromagnetic Waves by a Rectangular Aperture," IRE Trans. on Antennas and Propagation, V-AP4, 1956.

3-1A-2

# Diffraction of Planar Electromagnetic Waves by a Slot

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## ABSTRACT

An understanding of the basic mechanisms by which an electromagnetic signal penetrates an aperture in a shielded enclosure is prerequisite to the investigation of EMP interaction with devices and subsystems. Of all the aperture configurations that could be considered, the two-dimensional slot in a conducting screen is probably the most elementary. In fact, this particular aperture is one of the few shapes for which an exact solution can be specified. Unfortunately, the solutions take the form of very slowly convergent series if the characteristic aperture dimensions exceed one or two wavelengths of the incident wavelength. However, by the use of asymptotic edge-wave methods and the principle of superposition, it is possible to write a very simple code to compute the diffracted far field. Results obtained using this code are in reasonable agreement with experimental microwave measurements made in the Sandia Laboratory anechoic chamber.

# FIRST DISCUSSIONS IN GENERALIZING BABINET'S PRINCIPLE IN TWO DIMENSIONS

by

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ABSTRACT: We present our first investigations to thoroughly understand Babinet's principle for electromagnetic diffraction and the results of our initial efforts to extend the principle beyond its usual range of application. Proof is given that the principle in its present form is invalid for the general open, two dimensional, infinitely thin, perfectly conducting surface containing apertures. Our proof is independent of the type of incident wave (plane, cylindrical, parabolic, etc.) and its state of polarization. The only case in which the present Babinet's principle holds is the conventional one of an infinite plane. Recent investigations for a series of initial and complementary problems of particular shapes with apertures seem to imply the existence of a more generalized form. However, this phase of the work is still in the early stages of development.

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# SCATTERING BY THE LONGITUDINALLY SLOTTED CONDUCTING CYLINDER

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We present the results of investigating the response of very long, thin walled, axially slotted, conducting cylinders to normally incident plane wave irradiation polarized parallel to the cylinder axis. Utilizing field expansions, which satisfy the boundary conditions on the cylinder, integral equations for surface current as well as aperture electric field distribution were derived. Numerical results for the solutions of these integral equations have been obtained for extensive ranges of the physical parameters: wavelength, cylinder radius and slot size. Previously unknown requirements on the scattering coefficients at the waveguide eigenfrequencies have been developed and these will be discussed. The calculated slot electric field is in close agreement with results obtained by others over their range of validity and is an improvement over their results everywhere else. We present back scattering cross-sections for a large range of the ratio of radius to wavelength for slots varying from very narrow through the half-cylindrical mirror to the cylindrical ribbon. The behavior of the resonances as the slot widens will be discussed. For very narrow slots we present the first analytic results for the resonances which agree with experimental data.

Orlando Lopez

Kaman Sciences Corporation

# EMP COUPLING THROUGH A FLUSH MOUNTED COAXIAL APERTURE - VARIATIONAL CALCULATION

The coupling of EMP through the exposed multiconductor umbilical connector modeled as a flush mounted annular slot antenna with a connecting cable has been a subject of recent interest[1]. The work of Chang and Harrison[1] considers the case where the incident electric field does not lie on the plane of the aperture and the cable is long enough so that the TE and TM modes are completely attenuated. In cases of interest the cable is short and the incident polarization is such that the incident electric field lies on the plane of the aperture. (That is, the TEM mode is not excited). In this note we formulate the problem via a variational method similar to that used by Levine and Schwinger[2] for the analysis of diffraction by a circular aperture. The frequency response from $6 \times 10^6$ Hz to $4 \times 10^8$ Hz (for several angles of incidence) of a coaxial aperture which is mounted flush on a perfectly conducting plane, is obtained for the case in which the incident electric field lies on the plane of the aperture. A generalization of the method in order to include finite dimensions of the body on which the connector is mounted is discussed.

(1) D. C. Chang and C. W. Harrison, <u>IEEE Trans. on EMC</u>, Volume EMC-13, #1, Feb 1971, pp 14-18.

(2) H. Levine and J. Schwinger, <u>Comm. on Pure and App. Math.</u>, Volume 3, p. 355 and ff, 1950.

# BACKSCATTERING FROM A CIRCULAR PLATE BY WIRE MESH MODELING *

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In the study of vulnerability and hardening of an aeronautical system subject to an incident electromagnetic pulse (EMP), one is often confronted with solving the problem of scattering by apertures. A numerical technique was recently developed by Lin, Curtis and Vincent, determining the aperture field distribution by solving the complementary problem of the diffraction of a conducting plate modeled by a wire mesh. As an initial verification for the wire mesh model chosen, the far zone field is used to calculate the radar cross sections which are then compared with measurements made with a series of models consisting of both wire mesh and conducting plate. Since the technique mentioned above is successful in treating the case of a rectangular plate, an effort is now made to extend this technique to a circular plate in a hope that the same technique may be applied to the scattering problem with apertures of irregular shapes.

Consider a perfectly conducting circular plate of radius a modeled into wire mesh composed primarily of square grid with side $\Delta$ and wire radius $r_0$ encircled by a circular loop of radius a. A plane electromagnetic wave with E(H) field parallel to the plane of the plate is assumed to be incident on the plate at an arbitrary angle $\theta$. Numerical examples include the echo areas plotted as a function of incidence angle for E and H polarization at ka=4 where k is the wave number of free space. The calculated values are then compared with the theoretical and experimental results given by Mattson. (The theoretical results were obtained numerically on the basis of Flammer's exact solution.) It is found that the numerical results for a wire mesh model with $\Delta/r_0=25$ are almost the same as those of a solid plate for small incidence angles ($0 \leq 20°$); however, they tend to deviate as $\theta$ increases. This tendency is reasonable considering the difference between the discrete distribution in the wire mesh and the continuous distribution of current on the solid conducting plate as was found in the wire mesh model and the solid conducting rectangular plate. Radar cross sections of a circular plate are also calculated as a function of plate size, $a/\lambda$, for the normal incidence case. The calculated values compare well with numerical and experimental results presented by Richmond, in which his measurements were based on a solid conducting plate and his numerical results derived from a different wire mesh model with considerable more elements.

* This work was supported by the Air Force Weapons Laboratory, Kirtland AFB, Albuquerque, New Mexico, Contract F29601-72-C-0028.

3-1A-7

# ON EMP EXCITATIONS OF CAVITIES THROUGH SMALL APERTURES

by

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The problem of transient excitation of cavities by EMP fields through small apertures is studied based on Bethe's theory. This theory is extended in two respects: one is the study of damping due to the aperture on the cavity fields, and the other includes a procedure for calculating electric and magnetic polarizabilities of a small plane aperture with an arbitrary geometrical shape. The first extension is achieved through the use of a self-consistent scheme, which requires the field at the aperture to be the sum of the external and cavity fields. The comparison of the damping due to the conductivity and that of the aperture is made. In the second extension, calculations of a rectangular aperture is made, and a simple numerical scheme is described.

INTERACTION SECTION

Session 1B

Tuesday Afternoon 25 September 1973

Chairman: J. Bombardt
Harry Diamond Laboratory

# .EMP COUPLING TO CABLES INSIDE AN AIRCRAFT BY DIFFUSION THROUGH THE SKIN *

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The EMP coupling to a cable inside of an aircraft or missile is estimated by considering the aircraft fuselage or missile as a finite length cylindrical metal shell. Inside the shell is a single wire cable running parallel to but not necessarily on the cylindrical axis. The cable is loaded at one end and open circuited at the other end.

The exterior surface current and the internal fields of thin metallic shells consist of two dominant modes, a dipole mode and a loop mode. The field strengths at the inside shell wall due to the exterior loop current are identical for the spherical shell and the infinite cylindrical shell and they are assumed to be the same for the finite cylindrical shell. The interior fields due to the dipole currents are determined by a transfer function from the exterior dipole current. The dipole current is found by the method of moments. After the interior fields of the finite cylinder are determined, the open circuit voltage and the short circuit current can be found by considering the cable and shell as a transmission line and using the reciprocity theorem.

Numerical results indicate that the loop current fields dominate for typical aircraft dimensions except at the cylinder axis where the loop fields vanish. The effect of decreasing the shell thickness is to decrease the attenuation at all frequencies, particularly the higher frequencies. This shows up in the time domain by increasing the peaks, shortening the ries times, and decreasing the decay times of the internal signals.

* This work was supported by the Airforce Weapons Laboratory, Kirtland AFB, Albuquerque, New Mexico, Contract F29601-72-C-0028.

# SIMPLIFIED MODELING OF TYPICAL AIRCRAFT CABLES

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This paper presents some of the results from a study* of EMP coupling on typical aircraft cables. One purpose of that study which covers the material presented here was the development of simple models for predicting the equivalent circuit of any individual wire within the cable. The type of cable used in this study is typical of those found in existing aircraft and consists of bundles of insulated wires with one or more branches in the cable. Measurements were taken on several different configurations up to 12 meters long containing one or two branches mounted 2 inches above a flat metal ground plane and terminated with resistive loads including opens and shorts. The test cables were excited at a single point with a voltage common to each wire in the cable and measurements of open circuit voltage and short circuit current were made on individual wires over a frequency range of .1 to 32 MHz. Results are presented comparing the measurements with calculations from several different models of the cable systems for both voltage and impedance. One simple model considered which shows surprisingly good results related the equivalent Thevenin voltage to the common mode current on the cable and includes a simple single line model for common mode current. Also presented for comparison are calculations on a complete N-wire model of the cable systems using the computer code TRAFFIC.

Detailed conclusions are given for each of the models studied. In general it is shown that all the models show correlation to major variations with frequency except that in some cases the N-wire model was necessary to correctly model the low frequency behavior. Several important recommendations developed by this study are presented. An important one is the determination of limitations in the uniform N-wire line model because the cables are really not uniform.

* This work was supported by the Air Force Weapons Laboratory, Kirtland AFB, Albuquerque, New Mexico, Contract F29601-72-C-0028.

3-1B-3

# MODELING OF CONTROL-LAY CABLES, CONNECTORS, AND RACKS USING LUMPED PARAMETERS*

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This paper describes a procedure of developing lumped-parameter models for both symmetrical and unsymmetrical configurations of conductors and shields with an outer shield. The techniques described are used for modeling the cables in the Minuteman ground equipment. The required laboratory measurements are described and the basic formulas for determining cable parameters are explained. Whenever symmetry exists in a cable configuration, it is used to simplify the modeling process and keep the measurements to a minimum. A general model is made first, then it is reduced in size to represent a particular configuration. A computer program used for modeling the Minuteman Ground Support Equipment cables is presented to show how it develops the cable model and simplifies it in accounting for spare conductors, conductor grouping, shield grounding, and the handling of thru-braid coupling.

Cable connectors are included in the model. The method of treating the inner shields within the connector shell affects the shielding effectiveness and the resulting cross-coupling in the model.

Comparisons of computer and laboratory transfer functions to verify the models are presented. The models resulting from this process have the correct velocities of propagation and transfer functions for all conductor drive connections.

For modeling bundles of wires in a backplane of a rack, this paper describes three methods based upon:

1. Electrical Measurement of the Model Parameters
2. Dimensional Measurements on the Rack
3. Transfer-Admittance-Function Measurements

The advantages and disadvantages of each method are presented, and an optimum method, which combines the best features of each, is recommended.

* This work was supported by the Space and Military Systems Organization, Norton Air Force Base, San Bernadino, CA. Contract F04701-72-C-0210.

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3-1B-4

# Response of a Buried Cable to EMP From a High-Altitude Burst

Although the fields from EMP from a high-altitude burst (HAB) are weaker than those from a ground burst, they cover such a large area on the surface of the earth that it is important to know what voltage they may produce on the signal wires of a buried communication cable.

Working in the frequency domain, we find the internal leakage field in the cable from the incident EMP fields as a product of several transfer functions. Values of these transfer functions for various earth conductivities and for a typical communication cable appear in the unclassified EMP literature. We have convolved the transfer function and the spectrum of the incident pulse to determine core voltages in the cables.

3-1B-5

# MODELS OF TWO-CONDUCTOR LINES & BRAIDED-SHIELD CABLES FOR EMP INTERACTION CALCULATIONS

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Transmission-line equations can be derived to describe the interaction of a two-conductor line with an incident plane electromagnetic pulse, where the conductors can have different size [1]. Two source terms appear in the equations: a series distributed voltage source and a shunt distributed current source. The voltage source is equal to the time rate of change of the total magnetic flux minus the flux of the TEM mode resulting from the terminating impedances of the line. The current source is proportional to the time rate of change of the charge induced in one conductor of the line by the incident and scattered electric fields. Alternatively, this induced charge can be thought of as being proportional to the open-circuit voltage between the conductors caused by the incident electric field. For all practical purposes only one two-dimensional static boundary-value problem need be solved for adequately determining the coefficients and source terms in the transmission-line equations.

Transmission-line equations can also be derived for a braided-shield cable by modal analysis. In the case of good shields where only small hole coupling is considered important the two source terms in the transmission-line model depend on two parameters that describe the optical coverage and weave angle of the braid and also on the EMP induced current on the outer surface of the shield with all apertures short circuited [2], [3].

[1] K. S. H. Lee, IN 115.

[2] K. S. H. Lee and C. E. Baum, IN 132.

[3] R. W. Latham, IN 118.

# TRANSMISSION LINE MODELING*

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In this paper, two models of lossy transmission lines are compared from the point of view of computation time and accuracy. The goal is the Norton admittance representation of the transmission line as a function of frequency. Two approaches are compared. The multisection pi-section model, reduced to a Norton equivalent by a nodal condensation process; and the "exact" solution computed from the eigenvector transformation of hyperbolic function of the eigenvalues. If symmetry among the wires of the lines is not assumed, then the comparison involves the nodal condensation process of perhaps many pisections (depending on accuracy requirements, frequency range of interest, and accuracy) with the eigenvalue eigenvector computation. A recursive algorithm for nodal condensation is introduced which makes this approach favorable for up to 1000 pi-sections.

* This work was performed under Contract F04701-72-C-0210.

INTERACTION SECTION

Session 2A

Wednesday Morning 26 September 1973

Chairman: P. Randy Barnes
Oak Ridge National Laboratory

3-2A-1

# EMP Coupling to Power Lines

by

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## Abstract

A transmission line model of coupling to power lines has been developed that shows the effect of ground conductivity, angle of arrival, polarization, and power line geometry on the open circuit voltage at the end of the line. With this information, and the characteristic impedance of the line, the current and voltage to any termination may be calculated.

This theory has been checked with experimental measurements and shows quite good agreement with measured values of current. The measurements were performed on scale models of power lines. The soil conductivity was scaled appropriately. The results show that, although the transmission line model is not strictly applicable at the highest frequencies of interest, the error introduced by this approximation is less than the experimental error ( $\approx \pm 10\%$).

Measurements have also been made of the propagation of pulses down lines showing the effects of attenuation, dispersion, junctions, bends and spurs. Where available, theoretical calculations have been compared to measured results. From these measurements it is concluded that transmission line models can adequately be used to predict propagation effects.

# ELECTROMAGNETIC PULSE COUPLING TO POWER LINES*

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## ABSTRACT

The electromagnetic pulse-induced current in a single-phase power line is calculated by the application of both the electromagnetic scattering and transmission line theories. Scattering theory is used to calculate the current induced in an infinite wire with finite conductivity by a transient electromagnetic plane wave. The wire is located above and parallel to a non-perfectly conducting ground plane. The first-order effects of the ground are taken into account by including the ground-reflected incident wave in the solution of the induced current. Transmission line theory is then applied to compute the current in a line of finite length terminated by an impedance. The source terms of the transmission line equations are obtained from the results of scattering theory. By the combination of both the scattering and transmission line theories, the electromagnetic pulse coupling to a complicated configuration of finite lines with terminating impedance can be calculated.

*Research sponsored by the U.S. Atomic Energy Commission under contract with the Union Carbide Corporation.

3-2A-3

# COUPLING OF TRANSIENT RADIATED FIELDS INTO LINES


by

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## Abstract

A convenient analysis technique is derived for predicting the response of lines to transient radiated electromagnetic fields such as the electromagnetic pulse (EMP) associated with nuclear detonations. Simplifying assumptions, valid in the frequency range covered by the significant components of EMP, allow solution by means of a simple equivalent circuit. The circuit includes the effects of line losses and angle of incidence of the arriving field. Agreement with previously published results is shown.

# TWO DIMENSIONAL, TIME DEPENDENT COMPUTER CALCULATIONS OF CURRENTS AND FIELDS FOR A LONG WIRE PARALLEL TO A GROUND PLANE*

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INTELCOM RAD TECH

A new code, TEDIEM-3, has been developed in the TEDIEM family of time dependent 2-D IEMP codes. TEDIEM-3 calculates electric and magnetic fields and current transmission for the geometry of a long conducting wire parallel to a ground plane and connected to it by an arbitrary load.

The space, energy, angle, and time distributions of emission current are arbitrary. The Green's function technique is employed to determine the electric fields at each time step and finite "particles" of charge represent the primary current. Time dependent quantities of interest such as electric and magnetic fields, potential, charge and current densities are calculated.

Results are presented for the effect upon transmitted currents and electromagnetic fields of varying geometries, incident photon spectra, the load impedance, and the intensity of primary emission.

*This work was sponsored by the Defense Nuclear Agency under Contract DNA001-72-C0090.

# REFLECTION AND TRANSMISSION OF A TRAVELING WAVE AT A TRANSMISSION LINE - POWER TRANSFORMER JUNCTION*

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Distributed constant models are used to calculate the reflected and transmitted components of a delta function traveling voltage wave entering a power transformer winding from a transmission line. The solution is presented in terms of line integrals of functions defined in the frequency domain or alternatively in terms of convolution integrals in the time domain. It is shown how the models may be used to apply to the cases of traveling waves launched on the transmission line both by EMP and by lightning. Unpublished experimental work of Emberson and Emerle is reported which shows the onset of distributed constant behavior above 4 MHz in the transfer function of a 3 kVA power transformer.[1]

The distributed constant model of the transformer winding includes the effects of the winding inductance, the capacitance of the winding to ground, and the mutual capacitance of adjacent turns.[2] The model is meant to apply to one winding of a single phase power transformer. The effect of the other winding and its connections is ignored. The distributed constant model of the transmission line is the familiar one for which the phase velocity is independent of frequency. The transformer winding model has a phase velocity which decreases with increasing frequency before becoming imaginary at the resonant frequency of the tank circuit formed by the winding inductance and the mutual capacitance between turns. Both transmission line and the winding are assumed to be semi-infinite in extent so that waves reflected from terminations other than their mutual junction may be ignored. Aside from the necessary dependence upon position and time, the solutions for the reflected and transmitted waves are shown to depend upon a single parameter, which is a simple function of the circuit constants of the line and the winding. A discussion is given of the mathematical difficulties which arise when: (1) the winding is regarded as being finite in extent; (2) the variation of the winding inductance with space is included; and (3) the presence of the secondary winding and its connections is taken into account.

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*Research sponsored by the U.S. Atomic Energy Commission under contract with Union Carbide Corporation.

[1] W. C. Emberson and E. Emerle, "EMP Susceptibility Tests," IITRI Project No. E6216, Final Report for Period 29 October 1971-1 March 1972, prepared for Oak Ridge National Laboratory, April 1972.

[2] K. W. Wagner, "The Penetration of an Electromagnetic Wave into a Coil with Winding Capacitance, "Elektrotechnik und Maschinenbau, Vol. 33, 1915, pp. 89-92. Also (a) P. A. Abetti, "Bibliography on the Surge Performance of Transformers and Rotating Machines - Second Supplement," AIEE Transactions Vol. 83 pt. III (Power Apparatus and Systems), August 1964, pp. 855-858; (b) B. Heller and A. Veverka, Surge Phenomena in Electrical Machines, Iliffe Books Ltd., London, 1968; (c) L. V. Bewley, Traveling Waves on Transmission Systems, Dover Publications, New York 1951.

# EFFECTS OF RESISTIVITY ON THE CURRENT INDUCED IN AN INFINITE WIRE AND PROPERTIES OF THE TWO-DIMENSIONAL GREEN FUNCTIONS

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We consider a plane wave incident on an infinite cylinder of finite conductivity, and compare the induced current with that induced in a perfectly conducting cylinder. In particular, we consider an incident pulse that decays exponentially with time.

For a perfectly conducting cylinder, the late-time behavior of the induced current is a very slow decay proportional to 1/logt. In a resistive cylinder, the late-time behavior is that of the incident wave, in this case a decreasing exponential. If the conductivity is sufficiently large, we expect to find a region in time where the 1/logt behavior dominates.

In the case of oblique incidence, the current induced in a perfectly conducting cylinder diverges when the angle of incidence, measured between the direction of propagation and the wire, tends to zero. For finite conductivity, this current tends to zero with the angle.

These two differences illustrate the importance of the order in which the limits $\sigma\to\infty$ and $\omega\to 0$ or $\theta\to 0$ are taken.

We also exhibit some properties of the Green functions for the two-dimensional Helmholtz equation. It is known that they correspond either to incoming or outgoing waves, but for a complex constant the former decay exponentially with the distance from the source while the latter increase exponentially. Both solutions are unsatisfactory on physical grounds, but the latter can be more easily related to a physical situation.

A study of the energy balance shows that the energy propagating at larger distances comes from an infinitely remote source and is deflected outwardly; this hypothetical source also corresponds to fields increasing exponentially with the radius. We show that there is a region where the normal $1/\sqrt{R}$ dependence of the field predominates before the exponential growth sets in, and this corresponds to a meaningful radiation field.

INTERACTION SECTION

Session 2B

Wednesday Morning      26 September 1973

Chairman: Fred Tesche
Science Applications, Inc.

# DISTRIBUTED EXCITATION OF LINEAR RECIPROCAL CONDUCTOR SYSTEMS

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Electromagnetic excitation of linear reciprocal conductor systems is formulated in the frequency domain in terms of multiterminal Thevenin equivalents. Options and ambigueties in the definition of the "incident field" are discussed. Conditions for multi conductor systems to be describable as multi conductor transmission lines (MCT) are given. Special forms of Thevenin open circuit voltage for MCT's are given. MCT formulations using the inhomogeneous telegraphers equations are presented, with their limitations, for both single source and double source (series voltage and shunt current sources) models. The equivalence of these models is established.

* This work was supported by the Space and Military Systems Organization, Norton Air Force Base, San Bernadino, CA. Contract F04701-72-C-0210.

3-2B-2

# PARAMETRIC STUDIES OF EMP COUPLING WITH MULTICONDUCTOR TRANSMISSION LINES

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The matrix formulation describing electromagnetic field coupling with a set of parallel conductors is applied to study the EMP response of complex multiconductor transmission lines. Capacitive and inductive coupling parameters are determined by analytical approximations and by measurements for a seven conductor transmission line. A reference conductor is chosen, and the currents and voltages are computed in the terminating load impedances. The changes in response due to parametric variations in transmission line characteristics and illumination angles are presented. Application of the matrix method to the prediction of EMP response in complex cables employed in present day systems is discussed.

Sidney Frankel

Sidney Frankel & Associates

## Abstract

## Response of Quasi-TEM Multiwire Transmission Lines to External Fields

The behavior of a multiwire transmission line, operating in a nearly-TEM mode in response to an external monochromatic field, is evaluated by solving the inhomogeneous, first-order differential equations of the line through the use of Laplace transforms. Since, for a uniform line, the singularities of these transforms consist only of poles, the inverse transforms are readily evaluated by the method of residues. The poles of the transforms are the square roots of the eigenvalues of the line characteristic matrix, the multiplicity of any pole being generally equal to that of the corresponding eigenvalue.

The Laplace-transform attack appears to afford some advantage in directness of solution, and, for at least one important class of problems, in reduction in solution complexity compared to conventional procedures.

Multiple poles, resulting from the presence of degenerate modes, present no special problems; they are handled in a matrix extension of standard procedures for such poles.

When a number of poles are nearly equal, computational errors due to matrix ill-conditioning are avoided by expanding transform integrands in Laurent series around an "average" pole. The solution is in the form of an infinite series whose rate of convergence increases with decrease in dispersion of the eigenvalues.

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ABSTRACT: ANALYTICAL AND EXPERIMENTAL PROCEDURES FOR DETERMINING MULTICONDUCTOR LINE PARAMETERS

In any analysis to assess the vulnerability of an electronic system to a nuclear attack, the multiconductor cable proves to be one of the most significant collectors of electromagnetic energy. To determine the electromagnetic pulse response of any multiconductor line, the primary parameters, R, L, G and C must be obtained. This paper presents two new procedures, one analytical and one experimental, which overcome some difficulties encountered in using conventional techniques.

The analytical approach obtains the primary parameter values from a description of the cross-sectional geometry of a system of parallel conductors and is based, in part, on modified geometric-mean-distance formulations for inductance. The procedure has been automated in GROK, a user-oriented computer program that offers a variety of outputs to facilitate further processing. A principal advantage of this analytical approach is that a test sample of a cable is not necessary; only its dimensional specifications are needed.

Accurate measurement of multiconductor cable inductance and capacitance coefficients is difficult. The standard procedure is to measure the equivalent input capacitances between all pairs of conductors, and the phase velocity, in order to determine the inter-element capacitances and inductances. This procedure is very time consuming and not very accurate.

We present a new procedure which represents a direct extension to a well-known single-frequency technique for measuring the constants of a two-conductor line. It consists of measuring the input impedance between all possible pairs of conductors under both open-circuit and short-circuit load conditions. It then processes these quantities to yield the primary constants, phase velocity, and characteristic impedances of the line, as well as the shield transfer impedance. The advantages of the method are that it is unnecessary to measure the phase velocity on the line, and that all measurements are taken at a single frequency.

The parameters for several cables have been determined in accordance with the above procedures. Data is presented illustrating that both the analytical and experimental procedures yield parameters which are in very close agreement with those specified by the cable manufacturers.

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Multiconductor Transmission Line Theory And Experimental Verification

This paper develops a complete theory of uniform, multiwire transmission lines of arbitrary configuration. The developed equations include the complementary solution (electrical mode) as well as the particular integral solution (radiation mode). Hence, they are applicable to the study of multiconductor lines subjected to either distributed or point-source EMP radiation, as well as to the study of cables subjected to stimulus only at the ends. Although these solutions are applicable to multiconductor cables of arbitrary symmetry, the problem of obtaining the principal coordinate system which is necessary to uncouple the system of equations is by no means a trivial task. However, explicit solutions to this problem are obtained for two special cases: For cables with ring symmetry and for lossless cables of uniform but arbitrary symmetry.

The developed theory is compared with experimental data for specially constructed 2 and 4 wire, ring symmetric cables in a conduit. Transfer functions up to 100 MHz for direct- and cross-coupling in these cables are measured for various resistive terminations from short circuits to 1200 Ω. It was found necessary to model the stray reactance in the termination loops including the loop inductance, the stray capacitance to ground and the effective shunt capacitance of the carbon resistor in order to get the best agreement between theory and experiment. Excellent agreement was obtained for the direct-coupling transfer functions. The cross-coupling transfer function data comparisons were reasonable but by no means perfect. While the characteristic signature of the theoretically predicted cross-coupling data was evident in the experimental data, the two often differed by as much as 10 db. Possible causes for these differences are discussed in the paper.

Applications of this theory to EMP coupling problems of interest are discussed. The motivation for applying both the ring symmetric and the lossless line theories to real EMP problems are discussed in a qualitative manner.

# TRANSMISSION LINE MODELS FOR USE WITH CIRCUIT/SYSTEM ANALYSIS PROGRAMS+

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Interest in system level computer-aided transient analysis of systems required to operate in electromagnetic pulse environments is increasing. In order to predict system transient response, it is important to include transmission line models in the system models. The purpose of this paper is to describe new techniques for modeling multiconductor transmission lines in a manner consistent with the SCEPTRE computer program. The methods are amenable to modification for use with other available analysis programs. The approach taken has been to develop computationally efficient and accurate terminal models of multiconductor cables which can be inserted into overall system models. The models developed can be loaded at both the source and load ends with arbitrary nonlinear loads.

To develop transmission line models for use with computer-aided circuit/system analysis programs, it is necessary to transform the partial differential equations used to describe transmission lines to ordinary differential equations of a form compatible with the available analysis programs. The approach developed is called the orthonormal function method. The general concept of the orthonormal function method is to derive a set of transfer functions in the Laplace transform domain relating forward and backward traveling waves on the line to voltages and currents at the source and load ends of the line, approximate the transfer functions with Laguerre polynomials, and represent the resulting rational polynomials in the time domain with state variable differential equations. To accomplish this, a change of variables is used with the transmission line equations to develop the appropriate transfer function equations. The resulting transfer functions contain hyperbolic functions, and in order to represent them in the time domain, it is necessary to approximate them with a truncated series. An orthonormal set of Laguerre polynomials was chosen for this purpose. The orthogonality property allows convenient computation of weighting coefficients to minimize least square error.

For multiconductor transmission lines with the lines coupled to each other, the transmission line equations can be brought into uncoupled form through a change of variables by defining modal voltages and currents. From this point of view, an n-conductor line behaves like n separate two conductor lines, and the solutions are coupled only by source and load boundary conditions which convert the modal quantities to terminal voltages and currents. Thus, the multiconductor model is n two conductor models connected by boundary condition circuits.

## SUMMARY

The orthonormal function approach to modeling multiconductor transmission lines provides the capability for modeling the response of systems which contain cables using available computer-aided circuit/system analysis programs. The technique is computationally efficient and accurate and can be used to predict EMP system response.

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+This research was sponsored by the Defense Nuclear Agency and monitored by the Air Force Weapons Laboratory.

*Aerospace Corporation, El Segundo, California.

INTERACTION SECTION

Session 3A

Wednesday Afternoon 26 September 1973

Chairman: E. K. Miller
Lawrence Livermore Laboratories

3-3A-1

# THE SCOPE AND TECHNIQUES OF EMP INTERACTION

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In recent years EMP interaction has come of age. This paper first considers what the EMP interaction problem consists of and how it relates to other EMP technical areas.

There are various mathematical and hybrid mathematical/experimental techniques for obtaining analytical and/or numerical results which quantitatively establish the various appropriate interaction parameters. These techniques treat not only the actual obtaining of numbers, but the organization of the information into convenient and logical categories. The various techniques can be either "exact" or approximate, the approximate techniques being appropriate for special regimes of frequency and/or time.

One of the most important goals for the EMP interaction discipline is the division of the interaction of EMP with a complex system into different "levels" of EMP interaction. This division can be thought of as an EMP interaction chain or sequence. The total interaction problem is then considered to approximately consist of several sub problems, each of which is studied separately. The results of the sub problems are then combined to give an approximation to the total EMP interaction problem.

3-3A-2

TO BE ANNOUNCED

INTERACTION SECTION

Session 3B

Wednesday Afternoon 26 September 1973

Chairman: E. K. Miller
Lawrence Livermore Laboratories

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A theoretical analysis has been performed for the magnetic coupling of EMP induced surface currents into a flush mounted microwave horn altimeter. The analysis develops simplified models of the altimeter, examines the effects of the horn geometry, and considers the effect of the hole in the conductor perturbing the surface currents which drive the horn aperture.

Experimental measurements were performed by driving the antenna flush mounted in one plate of a parallel plate transmission line in the frequency range 1 - 100 MHz. A standard magnetic loop with the same area as the effective loop in the altimeter was used as a control, and the relative coupling measured in both amplitude and phase. With the horn oriented for maximum response, the measured coupling was 4% (-14 dB) as compared with a predicted coupling of between 5 - 7%. With the horn oriented for minimum response, the coupling was $\lesssim \sim 40$ dB or nearly the noise level of the measurement system.

The analysis results, which correlate well with the test data, indicate a previously neglected mechanism for significant EMP energy coupling to flush mounted antennas on both aircraft and missiles. The EMP field peaks far below the usual frequencies considered for exciting the antenna in its pass band. The resulting EMP induced voltages will, in general, produce voltages of sufficient magnitude to cause permanent damage to unprotected receiver components.

# QUASI-STATIC ANALYSIS OF EMP COUPLING TO A HORN ANTENNA

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## ABSTRACT

This paper considers the below-band response of a horn-type aperture antenna. The antenna is modeled by a spheroidal cavity whose aperture is coplanar with an infinite ground plane. The model discussed in this paper permits variation of depth-to-width ratio in order to approximate the shapes of different horn antennas. A quasi-static solution of Laplace's equation is given for the electrostatic or magnetostatic problem. The electrostatic problem is appropriate for horn antennas excited by stubs; the magnetostatic problem for loop-excited horns. The solution is carried out for a representative type of horn and results are discussed.

INTERACTION SECTION

Session 3C

Wednesday Afternoon 26 September 1973

Chairman: C. W. Harrison, Jr.
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# A Simple Procedure for Estimating the Current Induced on Cylinder-Like Conductors Illuminated by EMP

by

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## ABSTRACT

It is shown that for a class of cylinder-like conducting objects a set of simple analytical formulas may be used to obtain the induced currents when the objects are illuminated by EMP. First the conducting object is represented by a right circular cylinder. Thus the object must at least be similar to a cylinder. If the cross section of the cylinder-like conducting object varies over the axial length (as for a prolate spheroid for example) then an average radius is used. Simple formulas are presented for the axial current, the frequency of the late time current oscillation and the damping constant of the late time current oscillations. The foregoing formulas are valid only for thin cylinders, i.e. when $L^2 \gg a^2$, where L is the total axial length and a the average radius.

# THE EARLY TIME RESPONSE OF THE LOW-FREQUENCY VERTICAL RADIATOR TO A TRANSIENT ELECTROMAGNETIC PLANE WAVE*

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## ABSTRACT

The vertical tower radiator commonly used in low-frequency (LF) transmitting-antenna systems is idealized by a semi-infinitely long, perfectly conducting, circular cylinder erected perpendicular to a perfectly conducting ground plane. The cylinder is separated from the ground plane by a finite gap. The Norton equivalent current source for the cylindrical antenna is obtained from the exact solution of the electromagnetic interaction of an infinite cylinder in free space and a transient plane wave. The Norton equivalent admittance is obtained from the exact solution for an infinite cylinder excited by a uniform distributed source. The time domain solution of the infinite antenna is applied to the finite antenna for early times, i.e., times before the reflections from the ends of the finite structure have effect. The early time behavior of the current induced through a typical LF antenna load by an incident field with a double exponential time history is obtained.

*Research sponsored jointly by the Air Force Weapons Laboratory and the U.S. Atomic Energy Commission under contract with the Union Carbide Corporation.

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# Transmitting and Receiving Impulse Responses of Selected Straight Wire and Aperture Antennas with and without Reflectors

This paper presents the transfer function and impulse response relationships, and their experimental verification, of selected straight wire and aperture antennas in their transmitting and receiving modes, for all points in space, with and without associated reflectors. These antenna types include monopoles and dipoles, variations of the TEM horn, back-to-back TEM horns where radiation out of the sides is of interest, and large angled bicones.

The development of the relationships are based upon expressing the surface current (in the case of the straight wire radiator) and aperture voltage (for the aperture radiators) as a function of time and position over the radiating surface. These relationships were transformed into the frequency domain and operated on to obtain the respective magnetic and electric vector potentials. Performing the appropriate curl operation on these potentials produced the desired radiated field results. The receive mode relationship then followed by the method of reciprocity.

The verification of these relationships was obtained by fabricating the antennas and parabolic reflectors in various sizes, and exciting them with impulse-like voltage and incident field sources for the respective transmitting and receiving modes. The results demonstrate that the measured waveshapes can be predicted quite accurately with their magnitudes within a few percent.

The confirmed relationships presented in this paper should be applicable to the design of special purpose simulators, and wide banded field sensors since it provides transient and CW information. The relationships also apply well to the EMP interaction and coupling area since the impulse response of an antenna may be convolved with the EMP threat to obtain the antenna's terminal response.

# EMP RESPONSE OF CIRCULAR LOOPS*

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The current induced on a circular loop illuminated by an EMP is determined using the method of moments. The time-domain results indicate the excitation of dipole and higher order multipole modes as well as the circulating current mode. A comparison of the moment method results with those for a simple, low-frequency, small loop model is made. This comparison indicates that the low-frequency model can be used to estimate the actual peak loop current for large loops. The effect of resistive loading is included.

*This work was sponsored under AFWL Prime Contract F29601-72-C-0124, Computer Sciences Subcontract SC 0124-4.

# BAND LIMITED APPROXIMATIONS OF DIPOLE ANTENNAS WITH A FINITE NUMBER OF CRITICAL FREQUENCIES*

by:

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A dipole antenna, being a distributed parameter network system, has an infinite number of critical frequencies (poles and zeros) of its effective length and input impedance. For purposes of computer analysis of the response of an antenna to EMP, a band limited approximation with only a finite number of critical frequencies is normally adequate.

One advantage of the band limited approximation is that it leads directly to a lumped parameter network (LPN) representation of the distributed system. Such a network can be used in the transient analysis of nonlinear systems attached to the distributed portion of the system using computer programs such as SCEPTRE.

A band limited approximation uses only a finite number of critical frequencies. These critical frequencies must be adjusted in value to make the frequency response of the band limited approximation agree with that of the distributed system. It is shown that, in many cases, a simple parameter adjustment procedure is adequate for curve fitting. This procedure adjusts the poles to obtain coincidence of the maxima of the frequency response and the zeros to obtain coincidence of the minima.

*This work is supported by Harry Diamond Laboratories (Lab. 1000), Woodbridge, Virginia, under Contract DAAG39-72-C-0192.

# Computer Analysis of the Fan Doublet Antenna*

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The EMP response of the fan-doublet, an HF-VHF communications antenna which resembles a bow tie viewed from broadside, has been measured by Harry Diamond Laboratory using a biconic simulator which produces a peak field strength at the antenna of 5,600 v/m. Computations for comparison with the experimental data were performed, modeling the antenna with an integral equation approach in the frequency domain and Fourier transforming the data to the time domain to determine the antenna's transient response. Results were obtained for the antenna located in free space and over a finitely conducting ground plane, the latter employing a modified image approach based upon the Fresenel plane wave reflection coefficients to model the antenna-ground interaction. In both cases the exciting field was assumed to be a plane wave at broadside incidence, having an estimated electric field based upon near ground measurements of the tangential magnetic field.

Results of the calculations will be presented for comparison with the measurement. The effect of the ground reflected field will also be demonstrated. Possible refinements in the computer model to more realistically analyze the antenna-biconic system will be discussed. Finally, a simple method to estimate the antenna current will be shown.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

3-3C-7

# APPLICATION OF SINGULARITY EXPANSION METHOD TO THE LOOP ANTENNA

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Using the Singularity Expansion Method (SEM) introduced by Baum, a study has been made of conducting wire loops. It is shown that the modal currents are just the exponential functions in the Fourier series representation of the current. Corresponding to each modal current, there are an infinite number of complex resonant frequencies, whose location in the complex frequency plane suggests three separate categories of resonant frequency or pole types. The first category contains only one pole; the second, a finite number of poles; and the third, an infinite number of poles appearing in a layer extending to infinity.

An asymptotic formula for the "transfer function" between the excitation and the current response enables one to find the singularity expansion of the current. Furthermore, it permits location of the layer poles and their residues for large complex frequencies. It can then be shown that the convergence of the singularity expansion in the complex frequency plane is relatively slow. Nevertheless, one still obtains good time domain results with but a few poles except for very early times.

An extensive parameter study of the poles and their residues permits a time domain analysis of the loop antenna over a wide range of loop parameters.

INTERACTION SECTION

Session 4A

Thursday Morning 27 September 1973

Chairman: Dr. Leon Peters
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# TRANSIENT SCATTERING BY AN L-WIRE USING THE SINGULARITY EXPANSION METHOD

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As a simple model for calculating the transient scattering of an aircraft, an L-shaped wire is analyzed using the singularity expansion method (SEM). The integral equation for the induced current is a Hallén-type integral equation which differs slightly in form from Pocklington-type equations used previously. As a result, certain differences in the form of the singularity expansion of the current appear for early times. Using moment methods, the integral equation is solved numerically for the complex resonant frequencies, the corresponding modal currents and charge, and coupling coefficients for a number of configurations of the L-wire.

It is found that both the radii and the relative lengths of the arms of the L-wire have a significant effect on the damping constant associated with the complex resonances. The modal currents remain essentially sinusoidal, however, for all resonances which are essentially oscillatory.

The introduction of a ground plane causes a splitting of the free-space resonant frequencies or poles of the current expansion in the complex frequency plane. As the height of the L-wire above the ground is varied, various secondary poles appear to orbit about the free space poles.

Time-domain calculations have been made for an L-wire excited by a step-function plane wave. The results compare favorably with those obtained from the Fourier inversion of frequency domain data.

# Surface Currents Induced on Structures Attached to the Wing of an Aircraft

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## Abstract

The wing of an aircraft is modeled as an elliptic cylinder and the dyadic Green's function is employed to obtain a vector integral equation only over the attached structure to calculate the surface currents induced by an incident EMP. In order to calculate the eight components of the dyadic Green's function the following problems involving the Mathieu functions were studied: 1) the rate of change of the Mathieu functions to determine the appropriate number of integration points to compute integrals; 2) the analytic removal of integrable singularities; 3) the termination of infinite integrals; and 4) the termination of infinite sums.

The frequency range over which numerical results can economically be obtained is discussed in conjunction with the modeling and zoning of the attached structure. Some pertinent numerical results are presented.

# CURRENT AND CHARGE DISTRIBUTIONS ON AIRCRAFT

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This paper describes the interaction between an incident EMP and the overall external structure of an aircraft. The technique used is to model the aircraft with straight sections of cylinders which include representations for the swept wing and tail structure of the aircraft. Assuming only axial currents on each section, the model is solved numerically using WIRANT, a computer code utilizing a moment method based on point matching and pulse expansion functions. This approach is standard and is discussed only briefly to bring out the assumptions that have been used for this application. Calculations have been made on several different configurations which include the aircraft in free space by itself and connected to a second aircraft for refueling and with the aircraft sitting on the ground. Results are presented showing both current distribution and charge distribution for plane wave excitation at different incident angles, polarizations and frequencies. Also presented are typical results in the time domain when the incident wave is a double exponential pulse.

This work was supported by the Airforce Weapons Laboratory Kirtland AFB, Albuquerque, New Mexico, Contract F29601-72-C-0028

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# DETERMINATION OF THE EMP ENHANCEMENT FACTOR

## ABSTRACT

EMP signals recorded on a C-135 aircraft are discussed with respect to the difference in amplitude and phase characteristics from that of a free space signal. The enhancement factor is defined as the ratio of the normalized amplitude of the aircraft signal to the normalized amplitude of close-in sensors for a 2 MV pulsed antenna system. Three different close-in sensors were used to measure fields in excess of 10 kV/m. The radiation pattern was mapped in azimuth and elevation by the aircraft and the close-in sensors. The enhancement factor and the time rate of change of the EMP signal is seen to vary significantly with aircraft attitude and position.

3-4A-5

# THE SINGULARITY EXPANSION METHOD APPLIED TO DETERMINE CURRENT AND CHARGE INDUCED ON INTERSECTING THIN CYLINDERS

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Recently the singularity expansion method was developed for treating general scattering problems. Using the technique one may determine directly the natural or resonant frequencies of a conducting scattering object and the current distributions associated with these resonances. The time domain response of the induced currents on a conducting scatterer appears simply a summation of exponentially damped sinusoids, the amplitude of each being determined in a straight-forward manner.

The starting point for the subject study is the Pocklington-type integro-differential equation for the current distribution induced on a structure of intersecting thin cylinders that are solid conductors with flat end faces. However to derive the integro-differential equation certain considerations are made. The cylinders are required to be thin and the Kirchhoff current law is enforced at intersections of cylinders.

To apply the singularity expansion method the aforementioned integro-differential equation is cast into matrix form by using the method of moments. If a sinusoidal pulse expansion is used for the current distribution then no numerical integrations are necessary.

The behavior of the resonant frequencies has been studied as some of the parameters of the problem have been varied; e.g. the crossing point of the cylinders, the ratio of the cylinder lengths, the length/radius ratio of the cylinders.

The problem of intersecting cylinders has also been formulated and studied for one set of geometric factors including the effects of a perfectly conducting ground plane by means of image theory. While the same numerical techniques are applicable to this problem, interesting new effects are observed due to the presence of the ground plane.

3-4A-6

# A COMPARISON OF MEASURED AND PREDICTED CURRENTS ON PIPE MODELS OF AIRCRAFT STRUCTURES

By

J. Roger Hill

Captain Peter A. Swan

## Abstract

The currents and charge densities induced on L-wire, crossed dipole and aircraft configurations due to the VPD environment were calculated using the method of moments. These quantities were predicted both with and without the presence of a perfectly conducting ground plane at the appropriate location. The predicted quantities were compared with those measured in the pipe experiments, and agreement was found to be quite good in amplitude for both predictions, although the predictions without a ground plane produce wave forms which agree more closely with those measured. It was concluded that the poorer quality of predictions with the ground plane may be due to losses in the actual ground plane at the VPD facility.

INTERACTION SECTION

Session 4B

Thursday Morning 27 September 1973

Chairman: Lou Libello
Naval Ordnance Lab

3-4B-1

# INTERACTION OF CYLINDRICAL POSTS AND CLOSE IN EMP ENVIRONMENTS

By

D. E. Merewether

## Abstract

Due to nonlinearities in air conductivity the EMP environment exciting a structure near a nuclear burst can be influenced by the presence of the structure itself.

In this presentation we shall discuss two dimensional EMP field calculations in the presence of a cylindrical post. We shall illustrate when the interaction is important and how it affects currents induced on the post. Comparison with responses computed from an incident $E(t)$ and $\sigma(t)$ will be made.

# COMPARISON OF COUPLED RESPONSE DUE TO DISPERSED AND NON-DISPERSED EMP ENVIRONMENTS

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## ABSTRACT

This paper compares the dipole response when excited by the dispersed EMP environment to that produced by the non-dispersed high altitude EMP fields. This comparison is useful for planning proper instrumentation and test procedures for systems to be tested in the simulated dispersed EMP environment.

The induced center current of a conducting cylinder with $\Omega=6$ was considered. This current was characterized in the time domain by the dipole's impulse response. Step function response data in the Sandia EMP Handbook was fitted with a damped sinusoid. The derivative of this step function gives an approximate dipole impulse response that will yield accurate results for peak amplitude calculations.

The non-dispersed environment was characterized by a double exponential waveform. The response to this environment was computed by analytically convolving the double exponential with the dipole impulse response.

The dispersed environment was described in the time domain by its envelope and instantaneous frequency. Analytic expressions were available for the instantaneous frequency while the envelope data was in the form of a tabular listing. The dipole center current from this environment was also obtained by convolution. Use of the principle of stationary phase allowed this computation to be performed manually.

Both the dispersed and non-dispersed environments were scaled such that their spectral amplitudes were equal at 100 MHz. Then the response due to the two types of environments was plotted as a function of the dipole resonant frequency. For resonant frequencies in the approximate range of 200-500 MHz, the peak induced responses in the two cases were essentially equal. For dipole resonant frequencies less than 200 MHz, the calculations show that the dispersed environment results in responses up to four times that produced by the non-dispersed environment.

3-4B-3

# A COMPARISON OF CW AND EMP TEST DATA

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## ABSTRACT

The current induced at the center of a conductor parallel to a finite conductivity ground plane was measured using both Electromagnetic Pulse (EMP) and Continuous Wave (CW) techniques. Measurements were made for several conductor lengths and for various heights of the conductors above ground.

The two types of data were compared by first transforming the CW data into the time domain to determine the impulse response; the response to an incident EMP was then computed using the convolution integral. An excellent agreement of the two types of data was obtained when the measured incident EMP was used in the convolution integral for computing the EMP response.

# EMP Interaction With a Thin Cylinder Above A Ground Plane Using The Singularity Expansion Method

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Abstract

The singularity expansion method is employed to determine the transient response of a thin-wire scatterer arbitrarily oriented above an infinite perfectly conducting ground plane. An integro-differential equation is formulated for the current on the scatterer in terms of the complex frequency, $s = \sigma + j\omega$. The method of moments is used to reduce this integro-differential equation to a system of linear algebraic equations. The singularity expansion method is then applied to determine the exterior natural resonances of the scatterer, the natural modes associated with these resonances, and finally, the transient response of the scatterer to a unit step incident wave. The analytical and numerical techniques used to obtain the various terms in the singularity expansion representation of the transient response are discussed, and results are presented for several different orientations of the scatterer with respect to the ground plane.

# SEM APPROACH TO EMP INTERACTION CALCULATIONS FOR CERTAIN SYSTEMS

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In order to fully understand the effects of the nuclear EMP on different systems it is necessary to calculate transient electromagnetic interaction of a plane wave and a variety of differently shaped bodies. The recently developed Singularity Expansion Method (SEM) [1,2] has proven to be an effective method to numerically investigate and physically interpret transient electromagnetic scattering from finite bodies. One of the advantages of SEM is that it provides a means of characterizing the electromagnetic properties of a body with a set of complex numbers (the natural frequencies) and two sets of modal functions. These quantities are uniquely determined by the body itself and do not depend on the incident field. Once these quantities are known a wide variety of scattering problems can be solved without having to solve any boundary-value problems.

The systems analyzed here are somewhat idealized in that the shapes of the bodies are taken to be prolate spheroids and circular cylinders in free space or above a ground plane. The solution of these problems will, however, give a rather accurate estimate of the currents and charges induced on the surfaces of systems such as a missile when subject to a nuclear EMP. The solution of the problem of one cylinder above ground also makes it possible to quantitatively estimate the interaction of a missile and the wave guiding structure of a transmission-line type EMP-simulator such as ARES and ATLAS.

The analysis is based on the magnetic-field integral equation simplified to account for rotational symmetry [3-5]. The natural frequencies and modes are calculated for a wide range of values of the parameters describing the geometry. The step-function response of the system is constructed from the natural modes in the same way as in network theory, and the result is presented in the form of graphes for the time history of the current and charge at different positions of the scattering body. It is found that for moderate and large times only a few modes are needed to accurately describe the response of the system [3]. It is also found that the interaction of a body with the ground and/or a simulator structure can be accounted for by a simple shift of the natural frequencies of the body. The loci in the complex frequency plane of a few natural frequencies are presented with the distance between the body and the ground as a parameter.

[1] C. E. Baum, (1971, IN 88).
[2] L. Marin and R. W. Latham, (1972, IN 92).
[3] L. Marin, (1972, IN 119).
[4] L. Marin, (1973, SSN 176).
[5] L. Marin, (1971, SSN 136).

# AN ALTERNATIVE FORMULATION FOR A CLASS OF THIN BODY SCATTERING PROBLEMS ARISING IN EMP ANALYSIS

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In EMP analysis one is often interested in computing the time-domain response of electrically thin scatterers, such as sensor booms, and apertures is thin plates with or without a backing wall. Typically these problems are solved by first carrying out the computation of the induced current, or the scattered field, in frequency domain, and subsequently Fourier transforming these quantities via the use of the FFT algorithm. The upper frequency limit of this computation is determined by the pulse shape of the incident wave and this frequency is often in the resonance region. As is well known, the use of the conventional E-field integral equation technique for solving these electrically thin scattering problems is limited by the matrix size associated with the problem. Also, the E-integral equation contains differential operators that may lead to numerical instabilities unless properly interpreted.

In this paper we describe an alternate formulation for electrically thin, flat or circular cylindrical structures. For the aperture the equation reduces to a form that is simpler, and moreover, the kernel of the integral has an uncoupled form. This allows one to handle larger structures (or higher frequencies) than possible via the conventional integral equation approach.

For the cylindrical structure, decoupling of the kernel is again possible, at least for one of the current components. Also, the resulting equation is no longer plagued with numerical instabilities as in the case of the conventional integral equation.

Numerical results illustrating the use of the alternate equations for the aperture coupling and diffraction by a finite, hollow cylinder are included in the paper.

Dr. D. A. Still
Member of Technical Staff
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Autonetics Division

3-4B-7

The Application of Relatively Theory to External Coupling Problems

This paper presents a technique based upon the theory of general relativity and applies it to external coupling problems. The technique is applied to a case in which a non simple conducting geometry is illuminated by some given electromagnetic field. The geometry can be mapped to a simple geometry (such as a dipole) for which solutions can be obtained. The electromagnetic field becomes a spatially distorted field in this new coordinate system. The response of this simple geometry to this distorted field can then be computed using existing techniques and the response can then be mapped back to the real system of interest. This makes it possible to obtain the antenna response of relatively complex bodies.

The mapping technique makes use of the tensor properties of the electromagnetic field as expressed through the Minkowsky field tensor. The current and charge densities form a four vector contravarient first rank tensor. These tensors can be mapped from one system to another using appropriate transformations.

Several examples are presented for complex problems where this technique can be applied. One consists of a configuration of bent wires illuminated by a plane wave field. These wires are mapped into a system in which the wires appear as a dipole antenna. The response of this dipole is then computed for the distorted field in this coordinate system. Examples for other problems where this technique could be employed are also presented.

INTERACTION SECTION

Session C-1B

Thursday Afternoon 27 September 1973

Chairman: D. Merewether
Mission Research Corporation

ABSTRACT

# SHADOWING EFFECTS AND ELECTROMAGNETIC TRANSFER PHENOMENA ON A MISSILE

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During the test of the Spartan missile at the ARES EMP test facility two groups of results were obtained which, when isolated from questions of missile vulnerability, are of interest as experimental data for comparison with previously developed analyses. Measurements of skin current and interior cable current were carried out around the periphery of the missile when in a vertical position, with the vertical E-field vector parallel to its axis.

A variation around the missile periphery is in agreement with the theory of antenna shadowing developed by T. T. Wu. On the "shadowed" side of the missile some discrepancy exists. A second group of results involves comparison of the measured frequency spectra of currents recorded in certain interior cables with the dominant skin current resonant frequencies. These show the first and second stage missile resonances clearly reproduced on interior cabling. They also support the validity of an approximate Kirchoff-type analysis, using skin current resonances for calculating the excitation of the cable by field leakage through the missile joints. The transfer of skin current resonance frequencies to interior cabling was clearly observed in measurements on the first and second stages of the missile, which might be considered cylindrical dipoles (skin current). Measurements on the isolated third stage could not be made, but cable measurements do not show a strong enhancement of the third stage dipole frequency.

This paper is recommended for inclusion in technical area c (Interaction and Coupling) and will be classified Confidential.

C-1B-3

# ENHANCEMENT OF EXHAUST PLUME ELECTRICAL CONDUCTIVITY BY AN ELECTROMAGNETIC PULSE

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George W. Bechtold
Georgia Institute of Technology, Atlanta, Ga.

## ABSTRACT

The effects of a high level, short duration electromagnetic pulse on the electrical conductivity of a solid propellant rocket exhaust plume have been studied using a simplified analysis. The complex plume gas is replaced by a three component gas system. Transient response of plume conductivity was calculated assuming three stages of relaxation which were energy limited. Increases in either pulse magnitude or duration results in an increase in peak plume conductivity and favors formation of a higher conductivity region near the plume boundary.

# POSEIDON EXHAUST PLUME INTERACTION WITH NEMP (U)

R. W. Sutton
Kaman Sciences Corporation

High performance motor exhaust plumes, such as those of the POSEIDON motors, are calculated to have non-equilibrated $e^-$ concentration that tends to enhance macroscopically measured electrical conductivity. The conductive plume is many times longer than the missile structure and one might expect serious perturbations to the response of the missile on interaction with the nuclear electromagnetic pulse. It is predicted that structural currents in the aft portion of the structure can be appreciably increased, and that the response pulse is considerably lengthened. This poses possible problems for the electronic systems on board.

The basic approach to evaluating the significance of this EMP current enhancement in the POSEIDON has been simulation of the plume by electrical analog methods during proof testing; however, predictions of free-field currents have been made and compare reasonably well with the simulated currents.

# EMP COUPLING TO SATELLITES (U)

E. E. O'Donnell
Kaman Sciences Corporation

Theoretical predictions of EMP coupling require the environment (E), a coupling factor (C), and a mathematical product of environment and coupling. Thus, the current induced at a specific location is frequently expressed as

$$I(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} E(\omega)\, C(\omega)\, e^{-i\omega t}\, d\omega \qquad (1)$$

Since E is usually specified, and numerical Fourier transform techniques are well known, the difficulty lies in determining the coupling factor.

For satellites, however, the integral (1) includes the ionospheric dispersion term

$$\exp \left\{ i \left( \frac{L}{c} \sqrt{\omega^2 - \omega_p^{\ 2}} - \frac{L}{c}\, \omega - \omega t \right) \right\} \qquad (2)$$

which has the effect of causing the phase of the integrand to vary extremely rapidly with frequency, so that normal numerical integration techniques cannot be used. For slowly varying coupling factors, the resulting integral can be solved by the Method of Stationary Phase (MSP). MSP cannot be applied, however, if the coupling varies rapidly with frequency, as in the case of a filter near resonance.

In this paper, the integral (1), with the dispersion term (2), is converted to the form

$$J = e^{iF(Z)} \int_0^{(\Omega/2\pi)^2} \left[ G(Z+2\pi\sqrt{x})\; e^{iR(Z+2\pi\sqrt{x})} \right] e^{iF''(Z)\cdot 2\pi^2 x}\; \frac{dx}{\sqrt{x}} \qquad (3)$$

which is of the form $\int G(x)\, e^{ixy} dx$ and can be evaluated using Filon's method. Sample calculations on actual satellite hardware will be shown.

This technique suggests a method of qualifying a spacecraft for EMP without an actual dispersed pulse simulator. The coupling factor could be determined empirically by exposing the satellite in an existing simulator such as ALECS or ARES. The current induced by the dispersed field could then be computed, using the algorithm described in the paper. Spacecraft hardness could be determined by injecting these currents at the package level.

This type of program is now in progress. Experimental and theoretical results will be described.

ABSTRACT

# PLUME CONDUCTIVITY AND MISSILE SKIN CURRENT ENHANCEMENT

Stanley Schneider
Nuclear Vulnerability and Hardening
McDonnell Douglas Astronautics Company

The enhancement of the plume conductivity by the strong EMP pulse and the subsequent alteration of the induced skin current on the missile is shown. Typical plumes have peak conductivities of about $10^{-4} - 10^{-3}$ mhos/m. The increase in conductivity due to ionization by the free electrons accelerated by finite electric field pulses is calculated. The calculation allows for the competing energy absorbing non-ionizing processes (e.g., molecular dissociation).

An approximate treatment of the skin current integral equations indicates a conductivity of about 1 mho/meter is needed to significantly alter the skin current distribution on the missile.

A related estimate is then made of the air breakdown of the strong EMP field at various altitudes.

This paper is recommended for presentation in technical area c (Interaction and Coupling) and will be classified Confidential.

C-1B-7

# Obscure Cable Pick-Up Mechanisms

by

J.E. Bridges

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Abstract - Confidential
Paper - Confidential

SIMULATION TECHNOLOGY SECTION

SIMULATION TECHNOLOGY SECTION

SESSION 1A

Tuesday Afternoon    25 September 1973

Chairman: R. W. Latham
Northrop Corporate Labs

Joint EMP Technical Meeting
(Kirtland Air Force Base, New Mexico 87117)

# TRANSIENT RADIATION FROM A STEP VOLTAGE EXCITED RESISTIVELY LOADED LINEAR ANTENNA

by

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## ABSTRACT

The transient radiation from step voltage excited linear antennas loaded non-uniformly and continuously with resistance are investigated by numerical means. The antennas considered are thin cylinders excited symmetrically at the centers by slice generators. The loading is assumed to be symmetrical and it increases continuously towards the end-points of the antenna. By solving numerically a modified Hallen's integral equation appropriate for the loaded antenna, the current distribution on the harmonically excited antenna are obtained for different values of the loading and for different frequencies. The transfer functions of the antenna and the spectral densities of the radiated waveforms are obtained as functions of frequency and loading. Finally, the time dependent waveforms radiated by the antenna are obtained by using the Fast Fourier Inversion technique. The effects of the different antenna parameters on the radiated waveforms are investigated. Some of the results are compared with available analytical results. The implications of the results in the design of a pulse radiating dipole antenna are also discussed.

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# ON THE LATE TIME BEHAVIOR OF FIELDS RADIATED FROM A CRITICALLY DAMPED, RESISTIVELY LOADED, LINEAR EMP SIMULATOR

by

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## ABSTRACT

The late time characteristics of the transient fields radiated by a linear EMP simulator are dictated primarily by the overall length of the simulator and by the presence of any impedance loading along the simulator.

One method for analyzing the behavior of such simulators is to use the Singularity Expansion Method (SEM). In this method of analysis, it is possible to define precisely what is meant by a "critically damped antenna".

This paper outlines the method of analysis for treating this class of problems and then presents numerical results for the unloaded simulator, as well as for three different types of resistive loading.

Joint EMP Technical Meeting
(Kirtland Air Force Base, New Mexico 87117)

# TRANSIENT RADIATION FROM RESISTIVELY LOADED TRANSMISSION LINES AND THIN BICONICAL ANTENNAS

by

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## ABSTRACT

This paper presents a theoretical analysis of the radiation and reception of transient electromagnetic signals by resistively loaded transmission lines and thin biconical antennas. The resistively loaded transmission line analysis supplies a basis for the study of transients in antennas.

The transient analysis is done by means of the method of Fourier transform. The Fast Fourier Transform technique of truncating series of sinusoids provides some economy where numerical computations are needed for the transformations.

For discretely loaded lines it is shown that an inverse distribution of resistance is optimum, based on criteria of maximizing current on the transmission line while mizimizing reflections.

For a step voltage excitation, the resulting current waveforms along the line and the transient radiated fields are analyzed. The transient field of a thin biconical antenna in its transmitting mode and its transient response in its receiving mode are also analyzed via the vector effective height function of the antenna.

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# TRANSMISSION LINE MODEL OF RADIATING DIPOLE WITH SPECIAL FORM OF IMPEDANCE LOADING

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## ABSTRACT

This paper considers the far-field radiated waveform and field pattern from a long, thin, cylindrical antenna in the transmission line approximation when driven by a voltage generator of waveform $V_0u(t)$ where $u(t)$ is the unit step function. The antenna is loaded with an impedance which is taken to have the form

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

where $h$ is the antenna half-length, $\zeta$ is the absolute value of the distance measured along the antenna from the center, $Z_\infty$ is an approximate antenna characteristic impedance based on that of a long, thin biconical antenna, and $\delta(\omega)$ is a complex function of frequency. Analytical and numerical solutions for the far field pattern and waveform are discussed. In particular, the effects of resistive with parallel inductive loading are discussed.

# ON THE EARLY TIME TRANSIENT RADIATION FROM ONE OR MORE SOURCES OF FINITE DIMENSIONS ON A LINEAR EMP SIMULATOR

by
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## ABSTRACT

One technique for simulating a nuclear EMP so as to study its effects on various systems is to pulse excite a linear antenna. This radiates electromagnetic fields whose early time characteristics are highly dependent upon the localized source geometry, and whose late time behavior depends primarily on the resistance loading of the linear antenna.

In this papar, the early time radiated fields from one or more source gaps of finite width are presented. By assuming that the antenna extends to infinity, the oscillations in the late time response, caused by reflections at the antenna ends, are suppressed. One very useful geometry for the source region is the biconical section, which has been investigated by other investigators. By using a fixed number, N, of discrete source bands, it is possible to approximate the biconical field. This will be discussed and a comparison made with the actual biconical field.

# Input Admittance of an Infinite Cylindrical Antenna Having a Biconical Feed

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Abstract

An expression for the input admittance is derived which has all of its singularities analytically removed in order to make it accessible for numerical computation. This expression is derived by using two different representations of the azimuthal magnetic field, one valid in the bicone region and the other valid in the region external to the infinite cylinder. The expression for the magnetic field in the bicone region is a modal expansion with coefficients that are to be determined. It is shown that the input admittance is simply related to the first two coefficients in this expansion. The method of obtaining these coefficients essentially relies on equating the tangential magnetic and electric fields corresponding to each representation of the azimuthal magnetic field over a surface that is in a region where all representations are valid.

SIMULATION TECHNOLOGY SECTION

SESSION 1B

Tuesday Afternoon 25 September 1973

Chairman: Lennart Marin
The Dikewood Corp

# Electromagnetic Fields Near the Center of TORUS

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## Abstract

A mode theory is introduced to derive the solutions for the electric and magnetic fields near the center of TORUS. The field is decomposed into various Fourier modes which depend only on the coordinate system being chosen. Even if the antenna properties are unknown, one may still calculate the Fourier modes which are independent of source distribution and independent of the frequency dependent loading impedance. As the loading impedance and source function are determined, one can compute the excitation factor of each mode, which is related to the current distribution on the antenna. Loaded with a uniform resistance, the frequency response with a delta-function source and the transient behavior of the fields with a step-function excitation are shown for various cases. The possibility of extending the mode method to other symmetric types of antenna is also discussed.

# TEMPS
# (TRANSPORTABLE ELECTROMAGNETIC PULSE SIMULATOR)

WILLIAM PETTY
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TEMPS (Transportable Electromagnetic Pulse Simulator) is a complete system designed to provide a threat related test capability for exo-atmospheric burst EMP testing of surface systems. Under the sponsorship of the Defense Nuclear Agency (DNA) the Electromagnetic Effects Laboratory of the Harry Diamond Laboratories has developed the TEMPS and is presently responsible for its operation.

The TEMPS facility consists basically of a high voltage pulse generator, antenna system, antenna support structure, data acquisition and analysis system and necessary support systems to these prime functions. It has the capability of being transported, erected and operated on remote sites with a minimum of user support. The facility will provide the user an EMP test capability that previously was technically and economically unavailable.

CLASSIFICATION U

# TEMPS ENVIRONMENT

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The electromagnetic environment generated by the TEMPS simulator is described. In particular, the simulator's performance capabilities and the environment in the normal test area are presented.

The simulator's performance capabilities are described in terms of output variations as observed at a range of 50 meters as the simulator's controls are varied through their range of operation. The pulse variation is seen to be no greater than 5%.

The normal test area is that space bounded by $\pm$ 45° radials about the simulator's centerline and a range of 100 meters from the antenna. The environment in this area is described by a field map of the electric and magnetic field components. Along the centerline it is seen that the fields simulate a plane wave and that the free field follows a 1/R distance dependence.

CLASSIFICATION U

# EMPRESS Simulation Facility

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The EMPRESS (Electro Magnetic Pulse Radiation Environment Simulator for Ships) at Solomons, Maryland, is a sub-threat level simulator developed for performing coupling and susceptibility studies of electrical/electronic systems aboard ships. Two aspects of the Navy's problem dictated the design configuration. These were the world wide deployment of Navy ships and the targeting scenarios. Based on these requirements a simulation facility was required that could generate both vertically and horizontally polarized waveforms, and provide a near uniform field distribution over a large area.

The resulting design is a radiating wave type simulator which in the vertically polarized mode of operation utilizes a 100 foot high inverted conical monopole antenna top loaded by a 1300 foot transmission line to minimize ringing and provide the low frequency components of the pulse. In the horizontally polarized mode the 1300 foot transmission line is terminated at both ends and driven at the center by a biconic section, which also houses the pulser, as a dipole antenna.

This paper discusses the design considerations for the simulation facility antennas, high voltage (2 MV) pulser, and the high voltage terminations when operated in the horizontal mode. Further the paper presents data on the fields produced by the facility (field mapping data) and the field instrumentation developed for mapping these fields.

The final topic covered by the paper will be the use of the facility for testing shipboard systems and other systems on the land area, and the possibility for testing of airborne systems on a fly-by-approach. The instrumentation and other facilities available will also be discussed.

# ELECTROMAGNETIC PULSE RADIATION ENVIRONMENT SIMULATOR FOR SHIPS

by

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White Oak, Silver Spring, Maryland

ABSTRACT: EMPRESS (Electromagnetic Pulse Radiation Environment Simulator for Ships) is a test facility designed to provide a threat related capability for testing electronic systems aboard active ships from the fleet. This facility is located on Point Patience, a point of land which extends into the Patuxent River at the Solomons Branch, Field Division, Naval Ordnance Laboratory, near Solomons, Maryland. Ships as large as DLG class may be moored in deep water adjacent to this facility for testing. Actually, tests of coupling configurations, ships, and aircraft have been performed since the Fall of 1972.

EMPRESS is capable of operating in two modes. One mode radiates a vertically polarized field; the other radiates a horizontally polarized field. Two to three days are required to convert between modes. The configuration for generating vertically polarized fields consists of a pulse generator which drives the apex (near ground plane) of a top loaded conical antenna. The base (upward part) of the 30-meter high conical antenna is connected to a fringe field line. The far end of this line is terminated through 300 ohms to ground. The field radiated to the working area 300 meters offshore is a double exponential pulse with a peak greater than 2,000 volts/meter and a zero crossing of $\sim$ 200 nanoseconds. When horizontally polarized fields are desired, the pulser is converted from a conic structure to a biconic structure. This increases its length to 4.27 meters. The pulser is then installed in the center of the 305-meter long fringe field line 30 meters above the ground. Both ends of the line are terminated to ground; the conic antenna is not used. In this configuration the radiating system becomes a biconic dipole antenna. High frequency components are radiated by the biconic section; the lower frequency components are radiated by the dipolar arms. The field radiated to the working area is dependent on height above the water due to the water reflection.

The pulse generator used is the Pulspak 8,000 designed by Pulsar Associates, Inc. It consists of a low inductance Marx generator assembly which charges a mylar-dielectric peaking capacitor and then connects to the load structure via a two-megavolt gas dielectric switch. The Marx generator is composed of fifty Marx stages separated by pressurized spark gaps. The stages are charged in parallel to a maximum of 44 Kv, then fired in series by reducing the gap pressure.



CLASSIFICATION: Unclassified

# AIRBORNE MAPPING OF THE HORIZONTAL EMPRESS

by

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ABSTRACT: The horizontal electromagnetic pulse radiation environment simulator for ships (EMPRESS) was mapped at altitudes between 500' and 2000' above the line using a self-contained horizontally polarized direct E-field probe provided by the Denver Research Institute. This work was performed in July 1973 in support of TACAMO aircraft electromagnetic pulse (EMP) tests.

This paper reports on the methods and results of this mapping.





CLASSIFICATION: Unclassified

SIMULATION TECHNOLOGY SECTION

SESSION 2A

Wednesday Afternoon 26 September 1973

Chairman: Dipak L. Sengupta
University of Michigan

# Numerical Analysis of a Transmission Line EMP Simulator

Keith M. Soo Hoo, The Aerospace Corporation

A theoretical model is defined for an EMP simulator for testing EMP effects on high altitude satellites. The simulator is comprised of three parallel plate transmission line sections. The first and third sections are tapered to accomodate respectively a generator and a terminating resistor. This problem is analyzed in the frequency domain over those frequency components which are known to contribute most significantly to a typical EMP waveform.

The analysis uses a numerical technique to solve the basic problem of an unknown current distribution on a curved, tapered strip, excited by a known electric field. The unknown current is solved by the method of moments using triangular basis functions. To check the computer program, input impedances were computed for the strip dipole and the triangular dipole. It is shown that these solutions compare quite favorably with experimental results. Variations in the solutions are also demonstrated for these same cases when edge singularities are not taken into account in the analysis.

For the transmission line simulator, computed input impedance, VSWR, power dissipated in the terminating resistor, and the power lost to radiation are presented as a function of frequency. It is shown that at the higher frequencies the simulator becomes a good radiator. The computed current was also used to calculate absolute field distributions in any region of interest. The evolution of higher order modes is demonstrated by this calculation.

For a given set of simulator dimensions, computer costs and core storage increase rapidly with frequency. Computer costs can be kept to within reasonable limits by making use of reciprocity, geometrical symmetries, and simplifying assumptions. The maximum frequency is therefore determined by the maximum available core storage. A quantitative discussion is given of this high frequency limit and its relationship to simulator dimensions.

# TRANSIENT FIELDS OF PARALLEL-PLATE SIMULATORS

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Certain types of EMP simulators make use of a parallel-plate transmission line as a guiding structure for the electromagnetic field. For many types of cylindrical transmission lines the field distribution of the TEM mode is nearly uniform over a significant portion of their cross section. Therefore, the TEM mode provides a good approximation to the free-space nuclear EMP. The TEM mode propagates at all frequencies but for higher frequencies, higher-order modes can also propagate and may become important. In many cases it is desirable to launch fast rising pulses on these simulators. In doing so many higher-order modes may be generated and could introduce undesirable effects.

To develop a quantitative understanding of the relative importance of the higher-order mode contribution the transient response of a simulator consisting of two parallel wires is investigated. Each wire is fed by a step voltage generator. One reason for investigating this particular problem is that we can find an explicit solution of a transient problem with the assumption that the diameter of each wire is small compared to the distance between the two wires. It is believed that many properties of the higher-order modes that can exist on this simulator are shared by the higher-order modes that can exist on other simulators such as the ATLAS simulator.

The analysis is based on a solution of the Maxwell equations which can be obtained by employing Laplace transform methods [1]. The field can be represented by an integral and a sum in the time domain. Each term in the sum can be thought of as due to a mode. One mode is the TEM mode and it propagates with the speed of light. The propagation constants of the other modes are complex, i.e., each mode is attenuated as it propagates along the line. The frequency variations of the propagation and attenuation constants of some of these modes are determined for different values of the radius-to-separation ratio of the wires.

The time history of the current at different positions on the two wires is calculated when each wire is excited by a step-voltage source. Two different modes of excitation are considered (1) the two voltage generators have opposite polarity (push-pull) and (2) they have the same polarity (push-push). It is found that the current on the wires can be described accurately by the TEM mode alone after one transient time or so between the wires. This, of course, means that transmission line theory is applicable for times larger than the transit time across the structure.

[1] L. Marin, (1973, SSN <u>173</u>).

# A TECHNIQUE FOR COMPUTING THE MODE SPECTRUM OF A PARALLEL-PLATE WAVEGUIDE WITH SIDE OPENINGS

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Department of Electrical Engineering
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The finite-width, parallel plate waveguide finds use as an EMP simulator for measuring the scattering characteristics of an object. To recover reliable data from the measurements in this type of device, it is important to have the knowledge of its modal characteristics.

In this paper, the mode spectrum of a finite-width parallel plate waveguide is investigated using an semi-analytical technique, which is numerically quite efficient. It is assumed that the two plates are of identical width $\ell$, and are symmetrically located at $x = \pm b$. The guide is infinite along the y axis which is taken to be the primary direction of propagation.

The first step toward analyzing this structure is to view it as a closed waveguide with impedance walls at $z = 0$ and $-\ell$. Because the original structure is an open one, the impedance of these fictitious walls has both real and imaginary parts, though it is almost reactive for well-guided modes, viz., the modes that are propagating predominantly in the y-direction. The impedance description of these walls may be obtained by following a method due to Vajnshtejn for solving the Fabry-Perot resonator problem.[1,2]

Once the impedance representation of the fictitious walls has been determined, the transverse resonance condition may be applied in a straightforward manner to compute the complex propagation constants along the y-direction.

Numerical results have been obtained for some lower order $TM_{qm}$ modes (with respect to z) where q and m are the modal indices associated with the field variation in the x- and z-directions, respectively. The results indicate that for the same q, the phase constants of the well-guided modes do not critically depend on m. On the other hand, the attenuation constants, though small, increase with increasing m.

REFERENCES

1. L. A. Vajnshtejn, "Open resonators for lasers," JETP Soviet Physics, Vol. 17, pp. 709-719, September 1963.

2. T. Itoh and R. Mittra, "Resonance Conditions of Open Resonators at Microwave Frequencies," submitted to IEEE Trans. Microwave Theory and Techniques.

4-2A-4

# IMPEDANCES AND FIELD DISTRIBUTIONS OF CURVED PARALLEL-PLATE TRANSMISSION-LINE SIMULATORS

Tom K. Liu
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Los Angeles, California

In the design of parallel-plate transmission-line simulators, it is desirable to achieve a maximum working volume, inside which the electric field of the TEM mode is required to have a prescribed uniformity. In this report the use of curved parallel plates in the design of such simulators is considered [1].

The configuration studied in detail is that of two symmetrically located, circular plates biased at equal but opposite potentials. The problem is analyzed by means of conformal transformations. The optimum field uniformity is determined by varying the angle that the plates substain at the center of the structure. It is found that the optimum angle is $90^{\circ}$. Field distributions and impedances of this type of simulator are obtained and graphed.

[1] Tom K. Liu, "Impedances and field distributions of curved parallel-plate transmission-line simulators," Sensor and Simulation Note 170, February 1973.

James E. Faulkner
NDRC

# THE EFFECT OF MODULE SYNCHRONIZATION ON THE FREQUENCY DOMAIN OUTPUT WAVEFORM

Assume a pulser array of n modules. The purpose of the study is to determine how synchronization affects the frequency content of the waveform. The physical model assumes the modules act independently of one another and that each module makes an identical contribution to the waveform. Denote the waveform with synchronization and the waveform without synchronization by $V(t)$ and $V'(t)$ respectively where t is time measured from some fiducial. Denote the Laplace transforms of V and V' by $\tilde{V}(s)$ and $\tilde{V}'(s)$ respectively where $s = 2\pi jf$ is the Laplace transform variable. The function $\tilde{g}(s)$ is defined by

$$\tilde{g}(s) = \tilde{V}'(s)/\tilde{V}(s) \tag{1}$$

Under the conditions of the model, $\tilde{g}(s)$ takes the simple form

$$\tilde{g}(s) = \frac{1}{n} \sum_{k=1}^{n} e^{-st_k} \tag{2}$$

where $t_k$ is the firing time of the k'th module. The $t_k$'s are defined in such a way that if each module fires at its proper time, $t_k = 0$ for all k. Thus $1 - |\tilde{g}(2\pi jf)|$ is the fractional loss at frequency f of the frequency domain waveform (measured in volts/meter/hertz, for example). The study includes different values of n and different distributions for the $t_k$'s. For a given probability distribution of the $t_k$'s, the problem is deterministic for infinite n but probabilistic for finite n.

# IMPEDANCES AND FIELDS OF A PLANAR ARRAY WITH SOURCES TRIGGERED IN A PLANE-WAVE SEQUENCE

Tom K. Liu
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In certain types of transmission-line type EMP simulators, the sources are arranged to form a planar array. With proper triggering sequence of the sources, the source array launches a plane wave in a desired direction. This can certainly be achieved for frequencies such that the spacings between adjacent array elements are small compared with the free-space wavelength. Early time performace of the far fields from this type of source array has been investigated by Baum [1]. Here, an analysis is presented for a particular source array structure which one can determine explicity its performance for a broad frequency range. Explicit expressions for the currents on the source sheet, driving-point impedances, and radiation fields are derived. The behavior of grating lobes is also investigated.

The configuration under study is a periodic planar array of wire antennas. Taking the periodicity of the structure and the plane-wave triggering sequence into consideration, the magnetic vector potential is obtained in the Fourier Transform domain. This potential can be re-expressed in a space-harmonic form. The quantities of interest, namely, the currents and the radiation field are derived from the expression for the vector potential.

The expressions show that the main lobe is the only one that contributes to the far field at low frequencies (and consequently at late time). This main lobe is a TEM plane wave propagating in the desired direction. Grating lobes occur at higher frequencies, and their directions are frequency dependent.

[1] C. E. Baum, Private Communication, April 1973.

SIMULATION TECHNOLOGY SECTION

SESSION 2B

Wednesday Afternoon 26 September 1973

Chairman: Dan F. Higgins
Mission Research Corp.

# Performance of an Admittance Sheet Plus Coplanar Flanges as a Matched Termination of a Two-Dimensional Parallel-Plate Transmission Line

A.D. Varvatsis
Northrop Corporate Laboratories
Pasadena, California

Abstract

The reflections of a monochromatic TEM wave or a step-function TEM pulse from an R,L admittance sheet terminating the transmission line are calculated. These reflections can be minimized by determining the value of R through a low-frequency argument whereas the choice of L requires a parametric study for various values of L. Both the perpendicular and sloped admittance sheet cases are considered. For the latter case the reflections were calculated in a region where the usual transmission line TM modes exist, that is, everywhere except within the triangular domain formed by the sloped admittance and the lower plate. Parametric plots for various values of L and the inclination angle $\xi$ are presented of the field components of the reflected TEM and first four TM modes in both the frequency and time domain. The advantages and disadvantages of sloping the admittance sheet and the effect on the choice of L are discussed.

K.K. Chan, L.B. Felsen, S.T. Peng and J. Shmoys
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## Diffraction of a Pulsed Dipole Field at a Bend in a Perfectly Conducting Sheet

One type of parallel plane simulator is fed by a tapered transmission line that connects the parallel plate region to a localized source region. As a result, the input pulse emitted by the source encounters a wall bend discontinuity at the junction between the feed and test waveguides. In a first step toward analyzing the effect of the junction discontinuity on the input pulse, a previous investigation[1] has dealt with the diffraction of a plane unit step pulse incident normally on a bend in a single, infinite, perfectly conducting plane sheet. The present study represents a generalization to the case of a spherical incident pulse which more nearly describes the actual feed situation. The spherical pulse is generated by a combination of vertical electric and horizontal magnetic dipoles located on the sheet and excited in such a manner as to simulate a unit step plane wave field in the vicinity of the bend. The analysis proceeds by deriving first an exact closed form solution for the diffracted field due to an arbitrarily oriented electric or magnetic dipole with impulsive dipole moment. This solution is then integrated numerically with the temporal source profile required for plane wave simulation. Numerical results for the various field components are presented and compared with those obtained previously[1] for true plane wave incidence. Various special cases are also discussed.

[1] D.F. Higgins, "The Diffraction of Electromagnetic Plane Waves by Interior and Exterior Bends in a Perfectly Conducting Sheet", Sensor and Simulation Note No. 128, Air Force Weapons Laboratory, Kirtland Air Force Base, Jan. 1971.

# Reflection from an Array of Dielectric Posts

R.W. Latham
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Pasadena, California

## Abstract

The reflection of a plane wave incident on a two-dimensional array of infinitely long dielectric posts is investigated. The array is infinite in the direction perpendicular to the propagation vector of the incident wave. This array is considered to be a model of the wooden support structure of the ATLAS simulators. In accordance with this intended application, the maximum post diameter is assumed to be small with respect to both the wavelength of the incident wave and the minimum distance between posts.

The impedance per unit length of a single post is first defined and calculated. Next, the sheet impedance of a single infinite row of identical posts is defined, and determined in terms of the impedance per unit length of the individual posts. The reflection from several rows of posts is then examined. An explicit formula for the reflection coefficient is obtained for the case where each row of the array is modelled as an impedance sheet. The limit where the impedance sheet concept breaks down is pointed out, and a method for extending the simpler results to this more general case is indicated.

Joint EMP Technical Meeting
(Kirtland Air Force Base, New Mexico 87117)

# PARALLEL PLATE TRANSMISSION IN PROXIMITY TO AN INFINITELY LONG CIRCULAR CYLINDER

by

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## ABSTRACT

The effect of the impedance of a parallel plate transmission line in proximity to an infinitely long circular cylinder parallel to the plates is investigated. The investigation is limited to the case of TEM wave propagation, and the equivalent electrostatic problem is solved numerically.

Parametric studies of the impedance for the case where the axis of the cylinder is on the center plane between the plates are carried out. The change in the impedance due to the variation of pertinent geometric parameters is presented numerically and graphically. The charge (current) distribution on the plates and the cylinder is also presented.

Jiunn S. Yu, Boyd D. Boitnott and John C. Wirth
Braddock, Dunn and McDonald, Inc./ARES

# MEASUREMENT AND ANALYSIS OF REFLECTED AND DIFFRACTED COMPONENTS AT ARES AND ALECS

This paper is an attempt to characterize simulator environments at ARES and ALECS. Because of the lack of a high-voltage "impulse" generator for high-resolution capabilities, the EMP-45 pulser at ARES and the EMP-28 pulser at ALECS are used to probe their environments that include all possible scattering objects and the termination loads. Since the electromagnetic environments appear differently when viewed from different locations, two permanent "view points" are selected near the working volume of the simulator to obtain a fairly representative environmental description.

Both electric (E) and magnetic (H) field sensors are used simultaneously to obtain the time-domain EMP. Statistical techniques are employed to reduce random errors involved in measurements and digitizations. A set of practical assumptions is then made to define environmental noises in time-domain. The noises are shown to consist of scattered pulses that can be identified with various scattering centers of the simulator. The present analyses show that the ALECS environments exclusive of the termination section are relatively "clean" when compared with that of ARES. The effectiveness of termination sections has been described in both time- and frequency-domains. In addition to complex spectral densities of E- and H-fields, the wave impedance of EMP has been obtained to show clearly the effects of standing waves resulting from the incidence and scattered pulses.

The analyzed results are considered useful in assessing the two simulators' environmental qualities, and in providing design guides for improved EMP simulators in the future.

## SIMULATION TECHNOLOGY SECTION

SESSION 3A

Thursday Morning 27 September 1973

Chairman: Ian Smith
Physics International

# EMP SIMULATORS

J. C. Martin
Atomic Weapons Research Establishment

After a brief review of some of the main developments in EMP simulators to date, the author gives his personal views as to fruitful areas of development in the next few years. While this will be mainly restricted to high voltage post generators, mention will be briefly made of some of the difficulties facing more advanced post energy forces. Despite not being a USA tax payer, the author will be impertinent enough to suggest areas where basic research may well repay itself significantly or indeed be essential.

# SOME ASPECTS OF PULSED POWER FOR EMP SIMULATION

Ian Smith

Physics International

TITLE: Compact, Ultra-High Density Marx Generator

AUTHORS: Capt Daniel M. Strickland
Capt William L. Heatherly

Air Force Weapons Laboratory
Kirtland AFB, New Mexico

ABSTRACT: A Marx generator with the highest energy density ever achieved has been developed at the Air Force Weapons Laboratory. The unit, which operates at 2 MV in atmospheric $SF_6$, is 2 m long, stores 18 KJ and weighs 460 pounds. This energy density of 39 joules per pound is significantly higher than anything previously achieved. The design also incorporates several novel features: The stage capacitors are 100 KV plastic-cased units with a density of 100 joules per pound; grading is achieved by a technique utilizing split grading rings; and a conductive elastomer is utilized for charging and triggering resistors.

Because of its compactness, light weight, and atmospheric gas insulation this Marx design is ideally suited for a variety of applications such as bounded-wave and radiating EMP simulators, plasma devices, laser systems, and electron-beam devices. The modular nature allows the design voltage to be increased or decreased as necessary.

The unit has a demonstrated erection jitter ($1\sigma$) of less than 5 nsec over a three to one voltage range and consequently can be precisely time-tied to test sequences or other hardware.

# INDUCTIVELY COUPLED CURRENT INJECTION PULSERS THEORY AND PRACTICE

Thomas O. Summers
Albuquerque Division, EG&G, Inc.

Richard A. Hays
Air Force Weapons Laboratory

## ABSTRACT

Current pulses of pre-specified amplitude may be inductively coupled into cable bundles of unknown impedance using a clamp-on coupler. A development of the circuit theory behind this type of pulser is presented. The conditions to be met in achieving independence of injected cable current with respect to cable impedance are developed.

In principle, the pulser is quite simple; however, two practical problems of considerable significance must be solved to fully realize the advantages of this type of pulser. The first problem, the effective resistance of the switch is important only if slowly decaying ringing waveforms are the desired output. The problem is solved by appropriate choice of switch gap length, fill gas, and operating pressure. The second problem involves the choice of ferrite core material for use in the coupler. The trade-offs discussed are between coupler size, tolerable cable bundle impedance, operating frequency, ringing damping constant, price, and availability versus ferrite permeability and Q.

A model pulser having carefully measured characteristics is described. The results of field evaluation tests are compared to theoretical expectations.

# EFFECTS OF COAXIAL CABLES ON FAST-RISETIME, HIGH-VOLTAGE PULSES

Charles A. Frost
D. B. Westenhaver

Albuquerque Division, EG&G, Inc.

## ABSTRACT

A non-linear phenomena has been observed in coaxial cables transmitting fast-risetime, high-voltage pulses. This phenomena is believed to be due to corona that occurs in air spaces within the dielectric surrounding the center conductor and the cable shield. This paper discusses the effects of this phenomena, and it presents test results for various coaxial cables. The design of a cable to eliminate this effect is discussed, and the test results on an experimental cable are presented.

# DEVELOPMENT OF HIGH VOLTAGE DAMPED SINUSOIDAL GENERATORS

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This paper describes the performance of a unique design for damped sine pulsers and load coupling transformers that were developed to satisfy requirements for hardness testing of electrical/electronic equipment to the B-1 Avionics EMP specification. In addition to generating the pulse waveform for bulk cable current injection,

$$i(t)_{cable} = K1\ (f_o)_{Max} e^{-.115\ ft} \sin(2\pi f_o t),$$

it was required that the pulsers drive equivalent cable loads between one and one hundred ohms. Two pulse generation alternatives are examined and discarded:

Lumped constant networks that exhibit excessive radiation loss and low Q at high frequencies;

A modulated linear amplifier, that appeared to be relatively expensive and not available within the desired time frame.

Generation of fairly high amplitude pulses at higher frequencies (4 - 10 $MH_z$) is economically achieved with a cavity resonator configuration. Pulse amplitude is adjustable by controlling cavity parameters and output attenuation. Inductive coupling of damped sinusoids at high power (10 - 20 KW) over a .1 - 100 MHz band onto the transmission line or cable under test is accomplished with a broadband transformer. Bandwidth, coupling efficiency and impedance magnitude matching are optimized with a split core transformer employing a single-turn primary. Pitfalls encountered in the design of resonators and transformers are discussed.

This work was supported by The Boeing Company

# DESIGN OF POWER AMPLIFIERS FOR DISPERSED EMP SIMULATION

Harold T. Buscher
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## ABSTRACT

The results of an extensive design study are presented. A review of the state-of-the-art of megawatt-level, dispersed pulse generation and amplification has been performed, with special attention devoted to current simulator applications. System tradeoffs and overall design philosophy are explored for specific, distributed-amplifier configurations capable of producing threat-level field intensities in existing simulators. Technology areas requiring further R&D input are outlined with the intent of realistically estimating risks and alternatives now available in distributed-amplifier design.

# A 6-1/2 MV, FAST RISETIME EMP SIMULATOR PULSER (TEMPS)

H. Aslin
Physics International Company

The TEMPS pulser drives a terminated horizontal dipole simulator system conceived and specified by the Harry Diamond Laboratories, Laboratory 1000, and funded by the Defense Nuclear Agency (DNA). The pulser represents significant advances in the art of high voltage, low inductance pulser design and fabrication.

The pulser is a bi-lateral Marx generator-peaking capacitor circuit, switched in series with the load by means of a self-breaking uniform field, pressurized gas output switch. The pulser produces a peak output voltage greater than 6.5 MV rising in less than 8 nsec (10-90%). Pulser capacity is 2.5 nF yielding into the 120 ohm load a roughly e-folding pulse tail with decay constant equal to 300 nsec. Marx inductance is about 0.6 μH/MV; the lowest inductance Marx design of its type.

The 3.5 MV peaking capacitors are a modular design that combines compactness with low overall wave impedance, and low effective series inductance, their length being limited principally by surface flashover considerations within the Freon 12 environment.

# REPETITIVE 250 kV EMP SIMULATION SYSTEM

P. Champney
Physics International Company

A repetitive pulse simulator was designed by Physics International for use by the Armed Forces Radiobiology Research Institute, Maryland as a EMP simulator for biological tests. The system delivers 250 kV peak amplitude pulses at the rate of 5 pulses per second with a 5 nsec risetime and 5 to 600 nsec 1/e fall time into a parallel plate transmission line of approximately 100 ohm impedance. The fast risetime was preserved between the switch and the transmission line by the use of a transitive region formed by the energy storage capacitors, which have a wave impedance that matches the line. The peak field within the transmission line was approximately 450 kV/m. The output polarity was reversible and the output amplitude adjustable down to 10 kV peak amplitude. The pulser repetition rate was adjustable from 0.1 to 7 pulses per second with a single shot mode available. The pulser was required to be operated unattended on a round-the-clock basis and therefore had to be extremely reliable, with a low probability of failure. To date the pulser has successfully accrued a total of about $7 \times 10^7$ shots at maximum voltage.

SIMULATION TECHNOLOGY SECTION

SESSION 3B

Thursday Morning 27 September 1973

Chairman: K. S. H. Lee
The Dikewood Corp.

ABSTRACT

# ELECTRON BEAM SIMULATION OF INTERNAL EMP (IEMP) IN SCALED SYSTEM MODELS

Stanley Schneider
Nuclear Vulnerability and Hardening
McDonnell Douglas Astronautics Company

Roger Little
Simulation Physics, Inc.

An analytic and laboratory study of use of electron beams (35 ns rise time) in the 10-100 Kev energy range to simulate IEMP effects was performed. A discussion of the e-beam field generator (SPI-5000 and 2500) used is included. The characteristics of IEMP simulation importance are discussed including pulse width, spectral variability and beam area.

Experiments using a small scale cylindrical (4-1/3" diameter - 2.6" depth) cavity with variable air pressure and with cables of various shapes were performed for an electron beam energy of 12 $\pm$ 7 Kev. A comparison of theory to experimental results is made. The space charge limiting of the beam is shown at low pressures (.6μ Hg in air) and the gradual breakdown of the space charge barrier as the pressure increases with large pressure changes (in the 10μ - 100μ range). The enhancement and decrease in cable pickup is shown to depend on the cable geometry as the pressure and hence the transmitted electron beam current changes. The cable current signatures are shown to change in a predictable manner as the pressure varies.

Experiments using thin dielectrics in the cavity were performed showing transmitted beam current enhancement (even in a vacuum) by a mechanism related to the breakdown of space charge barrier by air ionization. The advantages and disadvantages of the electron beam IEMP simulation techniques are discussed.

This paper is recommended for presentation as a part of technical area d (Simulation Technology) and will be unclassified.

# PULSED ELECTRON BEAM GENERATION AND CHARACTERIZATION FOR IEMP SIMULATION

By

Roger G. Little

Simulation Physics, Inc.
Bedford, Massachusetts

Pulsed electron beams with the following range of characteristics have been generated and characterized for IEMP simulation:

Electron Mean Energy = 10 - 100 keV

Current Density = 1 - 150 A/cm$^2$

Area = 200 - 750 cm$^2$

Pulse Width at Baseline = 40 - 150 ns.

The beams are produced using d.c. charged, solid dielectric, pulse power technology. Thin foil and mesh anodes have been used for extracting the very low voltage electrons from the diode of the generator.

A number of diagnostic techniques have been developed for determining beam characteristics upon injection into IEMP cavities and monitoring cavity parameters. Diode current and voltage are used to construct electron spectra. Deposition profiles at cavity walls are unfolded for electron energy from which radial electric field strengths can be determined. Thin film dosimetry is used for current density maps. A center conductor probe has been developed for monitoring fields at the axis of an IEMP cavity.

This paper elaborates upon these electron beam generation and characterization techniques and shows representative IEMP cavity data.

SIMULATION TECHNOLOGY SECTION

SESSION 4A

Thursday Afternoon      27 September 1973

Chairman: K. S. H. Lee
The Dikewood Corp.

4-4A-1

D. F. Higgins, C. L. Longmire, and M. A. Messier

Mission Research Corporation

# SOME PRELIMINARY DESIGN CONSIDERATIONS FOR A SGEMP SIMULATOR FOR SATELLITES

One method of testing satellites for SGEMP effects is to place the satellite within a large vacuum chamber and irradiate it with an incident x-ray pulse. This paper discusses some preliminary design considerations for such a system. A bremsstrahlung x-ray source spectrum is calculated and absorption in the target and tank window are considered. Photoelectric production processes and their relations to the vacuum requirements are discussed. Various factors related to the vacuum tank size (e.g. DC capacitance, cavity modes, etc.) are also considered. Finally, techniques for minimizing the escape of photoelectrons from the tank walls and damping the resonant modes of the cavity are discussed.

# The Effective Radii Approximation for the Capacitance of a Body Within an Enclosure

R.W. Latham
Northrop Corporate Laboratories
Pasadena, California

## Abstract

A study is made of the effective radii approximation to the electrostatic capacitance between a metallic body and a metallic enclosure within which the body is contained. This approximation consists of a recipe for calculating the radii of two spheres equivalent to the body and the enclosure and then using the formula for the capacitance between two concentric spheres. It is applicable when the body is at the minimum capacitance position within the enclosure.

The study includes derivations of the order of magnitude of the error of the approximation as the size of the body approaches zero, both in the general case and in the cases where either the body or the enclosure is truly spherical. The accuracy of the approximation is also illustrated by a number of particular examples for which precise numerical calculations are feasible.

Methods of calculating the equivalent radii of enclosures are discussed, and a couple of examples of such calculations are mentioned. Ways of bounding the equivalent radii of enclosures are also considered.

# Capacitance Bounds for Geometries Corresponding to an Advanced Simulator Design

M.I. Sancer
Northrop Corporate Laboratories
Pasadena, California

## Abstract

The capacitance bounds obtained in this work are the capacitance values between surfaces that can be inscribed within or circumscribed about the actual surfaces corresponding to an advanced simulator design. This method of obtaining bounds allows one to compare the capacitance of certain geometries without even making a numerical calculation; however, numerical calculations can readily be performed for arbitrary geometries. To augment our method of obtaining bounds, we determine the capacitance between two nonconcentric spheres. This capacitance is in the form of an infinite series and it is numerically summed and plotted. A closed form approximation to this series is also obtained and its accuracy is demonstrated by plotting it for the same range of parameters that were used for the plots of the numerical sum.

# ELECTRON TRAJECTORIES IN THE VICINITY OF A WIRE MESH PLACED PARALLEL TO A PERFECTLY CONDUCTING GROUND PLANE

Donald E. Jones and Shyam H. Gurbaxani*

The University of New Mexico
Albuquerque, New Mexico

In this paper we present the results of theoretical and numerical analysis of the electrostatic field distribution and electron trajectories in the vicinity of wire mesh placed parallel to a perfectly conducting ground plane. This three dimensional problem was developed using superposition of two two dimensional geometries in the simplified version of line charges. The problem was generalized by considering finite diameter parallel cylinders as well as finite diameter cross-wire mesh using expansion in ortho-normal functions. The parametric study includes consideration of various kinetic energies, angles of departure, mesh apertures, etc. Significant results using staggered multiple cross grids will also be presented. Finally, the utility of such geometries as effective traps for multienergetic charged particles will be discussed.

*Presently at the University of California, Lawrence Livermore Laboratory.

# Study of a Charges Wire Grid for Reducing Electron Backscatter in EMP Satellite Simulators

F.M. Tesche
Science Applications, Inc.
Berkeley, California

## ABSTRACT

This paper presents a brief study of a wire grid designed to reduce electron backscatter within an EMP satellite simulator. The grid, which is maintained at a constant potential, is modeled by an infinite number of thin cylinders which are located parallel to a perfectly conducting plane at zero potential. The distribution of potential around and away from the grid is shown for one particular grid geometry, as are the trajectories for electrons being emitted into the grid region from the ground plane. Curves showing the fraction of electrons escaping to infinity as a function of the angle of departure and the initial kinetic energy are presented for various grid geometries and an indication as how to use this data in subsequent investigation is outlined.

SIMULATION TECHNOLOGY SECTION

SESSION 4B

Thursday Afternoon      27 September 1973

Chairman: Walt Ware
Kaman Sciences Corp.

# THE QUALITY OF EMP SIMULATION IN AND NEAR THE SOURCE REGION

W. R. Graham and R. R. Schaefer
R&D Associates

Various types of EMP simulators have been constructed and even more have been designed to simulate the EMP environment found in and near the source region of a near-surface nuclear explosion. In this paper the general characteristics of the source region are first described. Various electro-magnetic coupling phenomena which could affect systems which must survive the close-in nuclear environment are then reviewed. The similarities and differences between the modes of coupling driven by the source region environment and by various types of simulators are then compared. It is shown that while certain modes of coupling can be accurately excited by field simulators, additional modes of coupling are excited in the source region. It is concluded that considerable care must be exercised in relating the results of EMP field simulation experiments to predictions of close-in EMP coupling.

# THE TECHNIQUE OF ELECTROMAGNETIC SCALE MODELING FOR EMP SIMULATION

Joseph A. Kreck, US Army, Harry Diamond Laboratories

Abstract:

The paper to be presented summaries the successful 100:1 scale modeling experiment conducted at Harry Diamond Laboratories, Washington, D.C., in conjunction with DNA and DCA.

An electromagnetic scale model is a reduced size simulation of a real system where all physical properties are modified according to a "scale" transformation. The reduced size simulation gives significant cost savings and allows great flexibility in quantitative and qualitative measurement. It will be shown that accuracy and confidence levels are not among the scale parameters.

Briefly, the scope of this paper covers:

(1) the theory of scale modeling; it's credibility; qualitative vs. quantitative data;

(2) when scale modeling can and should be used (as opposed to analytics or full scale simulation); a tool for extrapolating data from other sources;

(3) evolving a transformation from full size to scale; the important scale factors;

(4) approximations;

(5) the results from simulating TEMPS.

CLASSIFICATION: U

TITLE: (U) EMP TESTING OF BURIED CONDUITS

AUTHORS: Huey A. Roberts, Ph.D., Edmund Seijo,
and Forrest J. Agee, Ph.D., Group 1040
Harry Diamond Laboratories

Buried conduit systems form an integral part of the EMP shielding in large hardened missile systems such as SAFEGUARD to protect the communications, control, and power cabling from NEMP effects. In order to initially verify conduit system hardness and to insure that it is maintained over the system life, non destructive testing techniques are being developed which will detect and locate flaws which could adversely affect EMP hardness and measure their impact on system hardness. Several testing techniques which have been developed in the HDL Periodic Integrity Maintenance effort are discussed and experimental data is presented from measurements taken on buried conduits.

CLASSIFICATION: U
SECTION: d

# CW TECHNOLOGY APPLICATIONS SUMMARY

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## ABSTRACT

CW evaluation techniques are being used throughout the EMP community as the means for more accurate predictions of currents and voltages at critical points within a complex system. The increasing applications of this CW technology are due primarily to the improved accuracy and engineering data content of the system transfer functions that are provided by CW. Further, the flexibility and adaptability of radiating and bounded-wave test systems makes CW a preferred choice over pulse-test systems for characterizing the response of linear systems. Hardware, procedures, data acquisition, and processing techniques have been developed to the point that CW systems deserve consideration for application to any EMP vulnerability and assessment program. This paper discusses the capabilities and limitations of both radiating and bounded-array CW systems.

# Testing Laboratories

Richard Gaynor
Martin Marietta Aerospace
Orlando, Florida 32805

All systems have to be tested for their survival in at least some natural and man-created environments. EMP and lightning environments are the subjects of interest of our electromagnetic pulse testing laboratories.

System designers use such laboratories for testing subsystems and small systems to full environments, but require the use of government facilities to test large complete systems to full environments. The forcing functions are given by specification or by laboratory data.

Our experience covers testing in a long-wire facility, current injection facilities and some government-owned facilities. Subject systems have been tested under the field environment, submitted to current pulses and damped sine wave current pulses. Finalized techniques are submitted with their capabilities, confidence levels, and limitations.

The impact of the other electromagnetic environments upon the testing process is discussed so that a comprehensive testing program is derived.

Problems not-yet-currently addressed, such as:

- Accuracy of threat definition
- Margins of test signals
- Confidence in data acquisition
- Overdesign margins
- Reliability of a system under threat condition

are briefly covered in the perspective of the testing philosophy.

Laboratory capabilities are discussed as function of those factors to bring to the EMP community's attention laboratory classification in relation to the requirements imposed on the systems.

# VERTICALLY-POLARIZED DIPOLE (VPD) EMP SIMULATION FACILITY

J. C. Giles
Albuquerque Division, EG&G, Inc.

## ABSTRACT

The VPD facility was designed and constructed for the AFWL by EG&G in 1971 and has been in use since that time for testing the effects of EMP on USAF aeronautical systems. The simulated electromagnetic pulse is produced by discharging a multi-megavolt pulser into a resistively-loaded monopole antenna over a conducting ground plane. The pulser/antenna system provides field strengths of up to 6 kV/m at the center of the test area, with pulse risetimes of less than 5 nanoseconds. The resistive loading of the antenna is designed to eliminate current reflections at the top of the antenna and, thereby, to provide a good approximation to an exponentially decaying waveform. The antenna is a flared cone design, which provides optimum impedance matching to the high-voltage pulser and enhanced low-frequency radiating performance.

The EM fields at several positions about the antenna have been measured and found to be in basic agreement with existing analytical models for such antennae. Near-field radiation terms have been studied, as have variations in peak field strength and risetime with radial distance, azimuthal angle, and height above the ground plane.

The facility includes two instrumentation bunkers that are used for operating the high-voltage pulser, the EM environment monitoring instrumentation, and diagnostic measurement equipment. The latter includes several X-band microwave data transmission links.

# E.M. PULSE PROPAGATION OVER GROUND

Howard Fowles
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Maxwell's equations for the fields radiated by a vertical dipole over finitely conducting ground are solved numerically in the frequency domain for plane and spherical earth geometries in order to specify the amplitude and phase characteristics of a groundwave propagation channel. The propagation channel impulse response function is obtained in the time domain by Fourier inversion. The calculated response functions are used in the convolution integral to predict the waveforms at distant field points for a given source pulse. The inverse problem of correcting recorded waveforms for propagation effects is accomplished by deconvolution techniques once the propagation response function is specified.

These methods have been used to determine the fields radiated by the DRI EMP simulator as a function of elevation angle from B-Dot loop measurements made near ground level. The calculated fields are compared with free field measurements obtained with the DRI Spherical E-Field sensor.

SIMULATION TECHNOLOGY SECTION

SESSION C-1A

Thursday Afternoon 27 September 1973

Chairman: A. A. Cooper
Sandia Laboratories

Richard R. Schaefer
R & D ASSOCIATES
Post Office Box 3580
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4 June 1973

# SOURCE REGION EMP SIMULATOR APPLICATIONS, SPECIFICATIONS AND FEASIBILITY

## Abstract

Existing EMP simulators do not apply to the exposure of systems and system components in the EMP source region. The range of applications of source region EMP simulation and the means of achieving source region simulation, both underground and in the laboratory, are discussed. Specifications for valid simulation in terms of photon flux intensity, spectrum, pulse shape, area, total energy, and ambient atmosphere characteristics are formulated. Finally, the feasibility of simulation in terms of existing technology is discussed.

# HARDENING TECHNOLOGY SECTION

HARDENING TECHNOLOGY SECTION

Session 1A

Wednesday Morning 26 September 1973

Chairman: Robert Pohl
R&D Associates

# A CW TECHNIQUE FOR LOCATING ELECTROMAGNETIC FLAWS IN A BURIED CONDUIT

Mark. A Dreger
D. B. Westenhaver

Albuquerque Division, EG&G, Inc.

## ABSTRACT

Buried conduits are often used to route signals between critical defense complexes. Flaws, which decrease the electromagnetic shielding of these conduits, can exist from numerous reasons -- including improper assembly, rusted or deteriorated joints, rupture from freezing, and breakage from excessive overburden. This paper presents a technique used to identify and locate an electromagnetic leak. A swept CW signal is used to excite the conduit, and a signal on a sense wire inside the conduit is used as a monitor. Transfer functions of amplitude define the magnitude of the leaks, while the phase data is used to determine flow location. Multiple leaks can often be identified and located with this technique.

# TRANSIENT UPSET TOLERATION AS AN EMP HARDENING TECHNIQUE

W. R. Graham
R&D Associates

Both transient circuit upset and permanent component damage can produce serious malfunctions in modern electronics equipment. Although the issue is not yet clear, it may be possible to design and select components which have a much higher threshold to permanent damage than to transient upset. If this proves to be possible, then a degree of EMP hardness would be achieved through designing systems to be completely insensitive to the effects of transient circuit upset.

A number of techniques have been developed for rendering circuits insensitive to transient upset. However, the capabilities, limitations, and penalties of these techniques are not widely known to the EMP community. Only in rare instances have these techniques been integrated into a system design so thoroughly that the resulting overall system was insensitive to transient upset.

In this paper the characteristics of the developed techniques for tolerating transient upset are described, various overall system design approaches are discussed, and the relation of specific upset toleration techniques to the system design approaches are illustrated.

# LIMITATIONS OF "SEAM SNIFFER" TECHNIQUES TO ESTIMATE SHIELDING EFFECTIVENESS OVER A BROAD FREQUENCY RANGE

by:

J. Bridges, V. Formanek, and P. Toulios
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The limitations,advantages of "Seam Sniffer" techniques are of interest to those within the EMP community. This widely used technique was initially designed to locate the more common defects in the walls of shielded enclosures during construction. Because of its success in this application, it has been suggested as a system for qualifying enclosure performance over the entire frequency range of 10 kHz to 15 GHz. The "Seam Sniffer" relies only on a 95-kHz, highly localized magnetic field penetration sensor, and the extrapolation of this single-frequency magnetic field measurement to other frequency regions is to be regarded with considerable caution by those considering this as the only test method for shielded enclosure performance.

Extensive theoretical analyses and laboratory experiments were conducted to evaluate the use of the "Seam Sniffer" technique for signals in the high frequency band and higher. Results show the "Seam Sniffer" to be a reliable tool for checking out enclosure performance during construction, if used with care. The "Seam Sniffer" may locate some, but not all, classes of penetrations or defects of the enclosure walls. The "Seam Sniffer" will locate a bad seam only if care is taken so that the main current flow is largely perpendicular to every seam. The "Seam Sniffer" will not locate small holes. For the higher frequency regions, the "Seam Sniffer" indications are not generally indicative of the many possible coupling modes into an enclosure. The most troublesome coupling modes from a "Seam Sniffer" viewpoint are those associated from the quasi-static electric field pick-ups, from waveguide below cut-off defects, or from cross-field quasi-static magnetic to electric mechanisms.

In conclusion, past experience indicates that the "Seam Sniffer" can be a very useful tool to assure proper assembly during fabrication of an enclosure. This is true only because it detects the bulk but not all of the more commonly occurring enclosure construction defects. Some of the non-detectable enclosure defects can be of great significance from an EMP hardening viewpoint. Therefore, the technique should not be used for final acceptance test purposes.

# NEMP INTERFACE FAULT DETECTION TECHNIQUE

by

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## ABSTRACT

NEMP — induced effects which could cause system malfunctions dictate the need for a NEMP Detector (NPD) to initiate circumvention of these effects within mission-critical subsystems. This NPD is capable of classifying and registering a NEMP effect at a threshold level which is directly correlated to a possible circuit functional failure, or "upset" level. The essential elements of the detector include a driver and receiver, connecting cabling, a RC network, a Hi-Speed Schottky Register, a detection alarm and a reset capability. The detection technique is unique in that it is located at the hardware level and requires no calibration because it is within the actual I/O circuits.

5-1A-5

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ABSTRACT: THE ANALYSIS OF CRITICAL CIRCUIT CHAINS

The derivation of upset thresholds of selected "critical" circuits is an integral part of an assessment program designed to determine EMP effects on an electronic system. Circuit analysis, whether computer-aided or not, is one technique by which the thresholds can be derived.

The critical circuits are in general not the interface circuits, but are connected to interface circuits by an identifiable chain of circuits.

The analysis of this chain of circuits, to determine characteristics of the input signal required to cause upset of the critical circuit, forms the topic of this paper.

When derived for the entire chain rather than for the interface circuit or critical circuit alone, the threshold characteristics include the transmission requirements of the chain, and therefore are more accurate than those for the single circuit alone. The concept of the chain of circuits also permits inclusion, if desired, of internal control levels to simulate the time window for which the circuit is critical.

Since the circuit operation within the chain is usually non-linear, the chain analysis lends itself to solution by available codes, such as SCEPTRE.

The paper describes the composition of the chains, the handling of branches to the main chain, the modeling of the chains, the significance of transient responses of the circuits in the chain and their contribution to the threshold characteristics. The advantages of the chain approach over the single-circuit approach are discussed with examples given in which an intermediate circuit within the chain is a significant factor in the determination of the threshold.

# ELECTROMAGNETIC PULSE (EMP) HARDENING OF A RECEIVER

by

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ABSTRACT: The particular receiver obtained for EMP hardening contained an old design antenna overload protection circuit (AOPC). The response time of the old AOPC is too long to be effective against EMP. It was decided that a zener diode - blocking diode clipping circuit connected across the AOPC input would be useful in limiting a fast EMP transient. As it turned out, the newer AOPC being designed at that time contained such a zener diode - blocking diode clipping circuit to limit short duration (50-60 milliseconds) radio frequency (RF) power overloads. The 1N4148 blocking diodes in this new on AOPC clipping circuit were found to have marginal power dissipation capability for EMP protection as well as inadequate power dissipation capability for the intended function of limiting the short duration RF overloads. Based on laboratory measurements of threshold power damage levels of various diode replacement candidates; EMP field tests on clipping circuits, spark gaps, and the entire receiver system; and clipping effectiveness tests on clipping circuits modified with various blocking diodes; suggestions are made for improving the EMP protective capability of the present clipping circuit in the new AOPC. The clipping circuit at the same time will have adequate power dissipation capability with respect to its intended function of protecting the receiver against short duration RF overloads.

Noel T. Peples



CLASSIFICATION: Unclassified

5-1A-7

MR. R. J. TILLERY

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**Hardening the Heavy Lift Helicopter**

ABSTRACT

The design of the Army heavy lift helicopter (HLH) is assessed to determine the inherent hardness to the effects of electromagnetic pulse (EMP) resulting from a nuclear burst. Methods of improving hardness are addressed. Information contained was developed from design practices and criteria originally prepared for the B-1 program. The recommendations should be considered as a possible means of achieving hardness, and not an absolute solution to complex requirements. A balanced, total systems approach which includes hardening can aid the prime mission of the Army heavy lift helicopter (HLH), even when nuclear weapons threats are not present, because hardening reduces susceptibility to all undesirable electromagnetic energy.

SECTION e HARDENING TECHNOLOGY

# EFFECTS OF BURST EMP OUTAGES IN COMMUNICATION SYSTEMS

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## ABSTRACT

EMP generally has dramatic effects on communications. Short of permanent damage to the physical systems, EMP can cause devastating interrupts on the communication channels whether they are cable systems, RF links, or combinations of cable and radio. Exoatmospheric EMP, for example, can conceivably blanket CONUS communications with a wide range of outages. Back of the envelope calculations reveal that high data rate digital systems will lose not just one or two messages, but entire files of data with high probability that these data are extremely critical in light of the fact that a nuclear war is either imminent or in process.

System planners often revert to retransmission of the lost critical data. The penalty for such a philosophy is message delays far in excess of what can be tolerated.

This paper discusses, surveys, and compares techniques developed very recently in information coding theory which detects and corrects digital channel burst errors like EMP. Channel errors in communication systems can be corrected using a number of rather simple approaches which result in minimum message delays and data processor overhead.

# INTERACTIVE GRAPHICS AS A TOOL FOR SYSTEM RESPONSE PREDICTION

by

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ABSTRACT: This paper will discuss the potential of using system response prediction codes such as SCEPTRE, NET-2, and CIRCUS II under control of interactive graphics for predicting electromagnetic pulse (EMP) generated system response. A five to ten minute film or slide show of the computer aided network design by interactive graphics (CANDIG) system developed at the Naval Ordnance Laboratory will be shown. CANDIG allows the engineer to perform circuit and system analysis with a computer simply by drawing his schematic on a cathode ray tube. With this system the engineer has the computer under his control without the need for programming knowledge. The timesaving features, the data management features, and the overall flexibility of CANDIG will be discussed.





CLASSIFICATION: Unclassified

# DOUBLE ONE-SIDED TOLERANCE TECHNIQUE FOR DETERMINATION OF CIRCUIT PROBABILITY OF FAILURE TO NUCLEAR ENVIRONMENTS *

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This paper is concerned with the general problem of determining probability-of-failure versus nuclear-environment-magnitude data, with confidence statements, for circuits and components of electronic systems. The specific problem addressed is that of obtaining the statistical assessment statements from data derived utilizing small sample destructive testing techniques. The technique developed incorporates statistical small sample theory as well as one-sided tolerance analysis methods. It is shown that, after determining the sample mean ($\bar{x}$) and the unbiased sample standard deviation (s) from the threshold data obtained during the small sample testing, two one-sided tolerance bound curves can be constructed. The lower bound probability-of-failure versus nuclear-environment-magnitude curve is developed from $(E_i, P)$ data pairs where $E_i = \bar{x} + K(n,P,\gamma)s$ and $K(n,P,\gamma)$ is the one-sided tolerance factor for sample size n, proportion 100P%, and confidence coefficient $\gamma$. The upper bound probability-of-failure versus nuclear-environment-magnitude curve is developed from $(E_i, \{1-Q\})$ data pairs where $E_i = \bar{x} - K(n,Q,\gamma)s$. A derivation is provided proving that the two bounding curves provide a confidence band with confidence coefficient equal to $(2\gamma-1)$. An example illustrating the technique is provided for a generalized nuclear environment.

* This work was performed under Contract F04701-70-C-0137.

HARDENING TECHNOLOGY SECTION

Session 1B

Wednesday Morning 26 September 1973

Chairman: Bob Pohl
R&D Associates

# KEY SUPPRESSION DEVICE PARAMETERS FOR EMP HARDENING

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## ABSTRACT

The electrical transients induced by EMP exhibit unique characteristics which differ considerably from transients associated with other phenomena such as lightning, switching, and circuit malfunctions. The suppression techniques developed to handle more common transients, though not necessarily the same devices, can be used for EMP damage protection. The suppression devices used for circuit level EMP protection are referred to as Terminal Protection Devices (TPD). Little detailed data describing the response of TPD's to EMP related transients have been published. While most vendors publish specifications for TPD performance, there is little standardization of parameters and TPD response models are not available. This lack of parameter standardization has resulted in a proliferation of test data that is sometimes conflicting and often not directly comparable. This paper derives and/or defines a consistent set of parameters based on EMP circuit hardening requirements and on measurable component parameters. Three sets of parameters pertaining to pertinent TPD functional characteristics were defined as follows:

- Standby Parameters
- Protection Parameters
- Failure Parameters

These parameters are used to evaluate a representative sample of TPD's and the results are presented in matrix form to facilitate the selection of devices for specific hardening problems.

# TRANSFORMER ISOLATION FOR EMP *

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The isolation provided by power transformers of a wide range of power ratings is of significant concern in the evaluation of the EMP impact on circuits and systems. For purposes of analysis a particular value of isolation has been assumed. To assess the validity of this assumption the common mode rejection of several transformers ranging in size from a small instrument unit to a 10 MVA commercial power substation transformer was tested using both pulse and C. W. techniques. The frequency range utilized was between 1kH$_z$ and 100 MH$_z$. Transforms and transfer functions were computed for the pulse tests. The effectiveness of Faraday shielding was examined and was observed to range between approximately 5 dB and 30dB depending on the particular transformer and frequency. The voltage transfer ratio for several transformers was found to be approximately -100dB at 1kH$_z$ rising through several resonances to as little as approximately -10dB above 1MH$_z$ in some cases, which is significantly less than the value generally used. Two-port admittance parameters were established and compared to common models. Significant deviations from a model were found in the region of the resonances.

* This work was performed on Contract DACA87-72-C-0002.

# DYNAMIC SURGE ARRESTOR MODELS FOR USE IN WEAPON SYSTEMS TRANSIENT STUDIES *

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Gas filled electrical surge arrestors (ESA's) have dynamic performance capabilities which provide protection against transient overvoltages in sensitive systems design. There are numerous types of ESA's commercially available. The Launch Facility of the Minuteman system contains four different arrestor types. In spite of their physical differences, their electrical behavior is fairly similar. It is, therefore, possible to develop a unified modeling strategy for translating carefully designed laboratory experiments into equivalent circuit models suitable for computer aided analysis. The main objective of the paper is to present such a strategy.

Toward this end, the modeling effort is divided into two parts. First, a low level ESA model is developed (in some cases by computer aided optimization techniques). This model represents the dynamic behavior of the ESA in the absence of a breakdown (firing). Then superimposed on the low level model in a model representing the non-linear behavior of the ESA gap during breakdown. The gap is modeled by a non-linear resistance representing a near infinite resistance (insulation resistance) to a circuit while unfired and a near short circuit (discharge resistance) when fired. In addition, various dynamic elements representing gap parasitics are included. Perhaps the most notable characteristic of the gap model lies in its ability to account for ESA "overshoots" occurring with the arrestor driven by voltage excitation functions in the kilovolt per nano-second range. This is a crucial parameter of any good ESA model and of critical importance to a designer who is using the gap for protecting sensitive components. Extensive laboratory data on the impulse ratios of the various ESA's (the ratio of the firing voltage due to an applied voltage pulse with a high rate of rise and the d.c. firing voltage) is used to arrive at a statistical gap model representing the correct formative time lag before firing.

Finally, model verification data is presented showing good agreement between experimental test results and computed results.

* This work was performed on Air Force Contract F04701-72-C-0210.

HARDENING TECHNOLOGY SECTION

Session 2A

Wednesday Afternoon 26 September 1973

Chairman: Vic vanLint
INTELCOM RAD TECH

# SPARK GAP DEVICES FOR ELECTROMAGNETIC PULSE (EMP) PROTECTION

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Washington, DC

The advantages and disadvantages of using spark gaps for Electromagnetic Pulse (EMP) protection are reviewed and practical applications are discussed. The results of pulse tests on various spark gap devices are presented. The tests were conducted to determine device turn-on times, rate of rise for breakdown device degradation levels, and quench under dc and ac bias. The frequencies for the ac bias ranged from 60 and 400 Hertz for normal power applications to 30 MHertz for communication equipment application. Recommendations are made for standard device manufacturer specifications for EMP applications.

Classification U

# "New Solid State Techniques for Electromagnetic Pulse Protection"

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Field-induced, rapid switching of the bulk-impedance has been discovered in several near-insulators in recent years. In 1969, the author initiated a study of these "bi-conductors", which formed the active part of novel solid state "switch" prototypes. The outstanding tolerance of some of the switches for current surges suggested their application to protect sensitive components from dangerous electromagnetic pulses.

Particular serious problems arise at inputs of communications and surveillance systems connected to large antennas or long transmission lines. A sharp electromagnetic pulse (EMP) of high energy content may be induced in such a large structure as the result of a nuclear explosion. The EMP energy must be prevented from reaching the sensitive parts of the equipment by means which have no significant effect on normal operations. A conventional "transient suppressor", while adequate for the protection of the power inputs, is not suitable for RF signal inputs mainly because of its high "off" state capacitnace, $C_o$, which would reflect or otherwise distort the signal. Closer analysis shows that EMP protective devices should be rated according to the ratio $I_s/C_o$, with $I_s$ representing the maximum tolerated surge current. "Distributed" devices with high $I_s/C_o$ ratios normally function as part of the distributed capacity of an RF system, causing no significant perturbation. EMP energy is induced in many parts of an RF system nearly simultaneously, so that the "threshold voltages" of several of the protective devices are exceeded. The EMP energy is thus absorbed or deflected at several points and its concentration, via echo and other effects, in any part of the system is prevented. Since several protective devices share the EMP energy, their Joule heating is reduced accordingly. It can be further reduced by using devices with low "on" voltages and thus absorbing most of the EMP energy in ballast resistors and in the RF structure itself. The latter also serves as large heat sink.

A distributed protective scheme as outlined here will continue to operate, and to protect, after the loss of one protective device, provided the latter has the "fail-safe" characteristic to remain "open" after having absorbed an oversize surge. The system can thus be optimized to cope with many "average" surges as well as with a few, impropable, "worst case" surges.

It is shown that gaseous or semiconductor junction threshold switching devices do not provide the combination of features necessary for the EMP protection of RF systems. Various metal oxide materials are promising candidates. Results to date concerning the best of these materials are discussed.

# CHARACTERISTICS AND APPLICATIONS OF METAL OXIDE VARISTORS FOR EMP HARDENING*

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This paper describes the significant electrical characteristics and protection device applications of a new high energy electrical transient suppression device known as a "Metal Oxide Varistor". This device offers a unique property of highly non-linear resistance (varistor) and large energy-absorbing capability. The metal oxide varistor, when connected in an electrical circuit, exhibits, over a wide current range, a power law relationship between the current (I) flowing through the material and the voltage (V) across the terminals. This relationship is in the form: $I = (V/C)^n$, where C and n are constants, reflecting composition and geometry parameters, and are primarily a bulk property of the material. The material iteself is bipolar in that the non-linear resistance characteristic holds for both positive and negative polarity current. Further, the bulk properties of the material provide an inherent high-energy-absorbing capability, because energy dissipation is evenly distributed throughout.

These properties make this material an extremely attractive candidate as a surge suppression device in power systems and as a protection device against high-frequency electromagnetic pulse-induced electrical transients. The high nonlinearity of the metal oxide varistor enables it to perform in a manner similar to back to back zener diodes in circuit protective functions. Because its electrical characteristics are a function of bulk material properties, the geometrical design of the material as a surge protection device is also quite flexible. The material can, therefore, be made in the form of cylinders, disks, doughnuts, squares and so forth, and its desirable electrical characteristics can still be maintained.

The conduction characteristics of the varistor material are dependent on the current density through the material and the material thickness between conducting electrodes. For a given current density the voltage clamping level of the device can be linearly increased or decreased simply by linearly increasing or decreasing the amount of varistor material between conducting electrodes. The metal-oxide-varistor material response itself is also suited for fast surges and electromagnetic pulse protection applications. Turn on or delay times have not been observed for rapid rise time pulses of amplitudes up to 200 amperes with 0.5 to 1 nanosecond rise times. Excellent agreement between the experimental data and the idealized material response model was obtained. A considerable amount of experimental data has been developed to characterize the material degradation as a function of high energy electrical pulses for pulse widths from 200 nanoseconds to 150 microseconds. Also, other material characteristics such as switching speed, capacitance, temperature stability, etc., have been defined and will be presented. Hardening applications currently being studied will also be summarized.

*This work was sponsored by the Electromagnetic Effects Laboratory of the U. S. Army, Harry Diamond Labs under Contract No. DAAG39-72-C-0179, DASA M PR Subtask 71-302.

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# THEORY OF OPERATION OF SPARK GAPS FOR EMP HARDENING

Classification: Unclassified

## A B S T R A C T

Modern gas filled spark gaps provide a valuable tool for EMP hardening of electrical systems. This paper discusses the theory of operation of spark gaps, compares their characteristics with those of other surge protection devices and presents guidelines for their proper application and installation.

# COMPONENT EVALUATION FOR TERMINAL PROTECTION

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A number of commercially available components have been tested for suitability as terminal protection devices. This survey included spark gaps, filters, avalanche diodes and various other semiconductor components. Square pulses of 50ns and 500ns duration and up to 11KV in amplitude, with rise times of about 2-4ns, were applied to the devices. Response time and energy leakage were recorded for each test. Insertion loss and approximate failure level were measured for each device. A comparative evaluation of all devices tested will be given. Some simple combinations of devices will also be discussed.

CLASSIFICATION: U

HARDENING TECHNOLOGY SECTION

Session 2B

Wednesday Afternoon 26 September 1973

Chairman: Victor van Lint
Intelcom Rad Tech

Robert J. Minniti, Jr. - Electronics Engineer, Dept. E411
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# INVESTIGATION OF SECOND BREAKDOWN IN SEMICONDUCTOR JUNCTION DEVICES

## ABSTRACT

An important effect of the EMP is the inducement of large voltages across and currents into a junction type device. For sufficiently high magnitude (induced) pulses the junction device will be driven into a second breakdown mode. If this mode is sustained at high power levels failure of the junction will occur.

In the past several models have been advanced in an attempt to describe the second breakdown and failure phenomena. These models have shortcomings in that they do not describe the phenomena fully or accurately. This paper presents two models that describe second breakdown as a thermal problem. They are extensions of Wunsch's thermal model and overcome the shortcomings of prior models. They lead to mathematical formulations that accurately predict the delay times before the onset of second breakdown for various power levels applied to the device. The power-time relationships are found to have three distinct areas of dependencies. The power is proportional to $t^{-1}$ for very short delay times; it is proportional to $t^{-1/2}$ for intermediate delay times and is constant for long delay times. The various areas are found to be related to easily obtained device parameters.

The formulation is obtained in series form and subsequently simplified. The simplified forms are then used to predict the time delay before onset of second breakdown for a given power applied to a junction device. This formulation accounts for geometrical variations between devices, and is in closed form, thereby, greatly increasing the utility of the formulation. The B-E junctions of three transistors, each having different geometries, were tested and found to follow the predicted values. Also, a theoretical prediction is made and compared to data obtained elsewhere for a diode with a 100 volt reverse breakdown voltage.

# SUSCEPTIBILITY OF SEMICONDUCTOR DEVICES TO PULSE POWER DAMAGE

by

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ABSTRACT: A method for determining the susceptibility of semiconductor devices to damage from an electromagnetic pulse (EMP) is described. The method can be used as a nondestructive screening test. It is based on the increase in junction reverse breakdown voltage with temperature and can be used to find the most EMP resistant devices of a given device type. The junction is pulsed with a constant current pulse of desired width and of amplitude sufficient to cause junction heating, but safely below the burnout level, (which must be independently determined) so as not to stress the device. The increase in breakdown voltage due to the temperature rise divided by the room temperature breakdown voltage ($\Delta BV/BV$) is determined. Care is taken not to include the so-called walk-out phenomenon, space charge effects, etc. in the measurement. To apply the test, a portion of the device samples must be pulsed at the threshold burnout level. The experimental results are that those devices with high and low values of ($\Delta BV/BV$) are resistant to pulse power damage, while those with intermediate values are more susceptible to pulse power damage. The range of those ($\Delta BV/BV$) values associated with susceptible devices is determined, and devices with higher or lower values of ($\Delta BV/BV$) are accepted. These results can be derived with the aid of a model which assumes current constrictions to occur in low resistivity filaments through the junction. The assumptions of the model are approximately valid up to the very high temperatures which cause permanent junction damage. While previous investigators[1,2] have developed methods to determine the most EMP resistant device types, the present results provide a test to determine the most EMP resistant devices within a given device type. Also, in contrast to other tests[2], short pulse width tests can be run directly, with no need for extrapolation from longer pulse width data.

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[1] D. C. Wunsch and R. R. Bell, "Determination of Threshold Failure Levels of Semiconductor Diodes and Transistors Due to Voltage Pulses," IEEE Trans. Nuc. Sci. 15, 6, pp. 57-69, Dec 1968.

[2] D. M. Tasca, J. C. Peden, and J. Miletta, "Nondestructive Screening Test for Thermal Second Breakdown," IEEE Trans. Nuc. Sci. 19, 6, pp. 224-259, Dec 1972.



CLASSIFICATION: Unclassified

# INVESTIGATION OF ELECTROMAGNETIC PULSE (EMP) RADIATION EFFECTS ON ELECTROEXPLOSIVE DEVICES (EED'S)

by

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ABSTRACT: The EMP effects on EED'S have been investigated. The investigation was performed in two parts: (1) A variety of EED's were tested in the EMP field produced by a high level EMP simulator; (2) data of the physical and electrical characteristics were collected along with typical applications of the particular EED's.

The testing was performed at the Electromagnetic Pulse Radiation Environment Simulator for Ships (EMPRESS) Facility at Solomons, Maryland. For these tests the pulser and simulator cone assembly were oriented to produce a principal electric field in the vertical direction. The normal mode of operation was to fire the pulser to produce an electric field of $\cong$ 50 KV/meter and a magnetic field of 133 amperes/meter at the test location. The EED's were irradiated in various test configurations to evaluate both their failure threshold levels and their most susceptible failure modes. The results of this testing are discussed in some detail together with some broad guidelines for the design of EMP hardened EED's.

Noel T. Poplis



CLASSIFICATION: Unclassified

# DAMAGE THRESHOLDS OF P-N JUNCTION DEVICES BY A CURRENT PULSE METHOD

by

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ABSTRACT: In the most common method of determining damage thresholds of junction diodes and transistors, a square-topped voltage pulse of reverse polarity is applied to the p-n junction of interest in series with a limiting resistor. At the damage threshold the p-n junction goes into second breakdown, and permanent damage results if the power input is allowed to continue. The limiting resistor is usually mode comparable to the resistance of the avalanching diode, so the power applied remains more or less constant. The constant-power method of pulsing has the advantage that the onset of second breakdown is indicated by a sharp drop in diode reverse voltage and a simultaneous increase in current. But the process of switching into the diode's negative resistance mode is both very fast and very destructive. The current increases to the point where far more than threshold damage is done. Post-damage electrical measurements can do little or nothing to establish a threshold damage probability cure. Instead, the constant-power pulsing gives a go-no-go power level, below which no damage occurs and above which the diode is destroyed. No use is made of the fact that a continuous range of damage can be observed, going from subtle subthreshold effects to complete melting. Better results, in establishing a threshold damage level with some degree of confidence, can be achieved by pulsing the p-n junction into its negative resistance regime with a constant current source. The diode voltage drops from a high voltage turn-on point to a static operating point, and the current is not allowed to increase. This type of pulsing is less destructive and permits meaningful post-damage electrical measurement. The threshold damage level of a transistor type, at a given pulse width, can be arrived at by plotting percent degradation of gain on probability paper as a function of pulse power. The percent degradation in reverse breakdown voltage of a diode can be used as its damage indicator. At the high avalanche currents needed to produce damage by submicrosecond pulses, the resistance of the device is only a few ohms. Then a transmission line pulser with a characteristic impedance as low as 50 ohms can be used. In practice, a device is placed in series with the termination resistor of the transmission line, and pulse of the order of 100 volts is sent down the line. The device is rapidly switched into its low impedance mode by the excessive voltage during the pulse risetime. During the remainder of the pulse, the device causes only a slight mismatch to the line and yet receives a constant-current pulse.

CLASSIFICATION: Unclassified

# MODELING OF EMP INDUCED RESISTOR DAMAGE

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## ABSTRACT

Low power precision resistors are found in increasing number in state-of-the-art circuit design. Limited tests have shown that these devices are susceptible to damage at the pulse power levels associated with EMP. This work represents an evaluation of the response of these resistors to short time duration, high energy pulses. Increasingly sophisticated heat flow models for the resistor failure mechanism were derived and compared against experimentally obtained data.

Five resistor types, namely metal film, carbon film, metal oxide, carbon composition and wire wound were examined using pulse generators of the Velonex 350, or BDM SN/SPG-200 type. Data was taken at pulse widths of 0.1, 1.0, 10 and 100 μsec with stepped power levels until failure occurred. The theoretically derived models all assumed that resistor degradation is related to melting of the resistive material. Boundary value solutions to the heat flow equations were found for three configurations:

(1) An infinite thin cylindrical shell of resistive material.

(2) An infinite thin cylindrical shell of resistive material encasing an infinite cylinder of substrate.

(3) The same as (2) except that the resistive material is spiraled.

The more sophisticated of these models are shown to agree quite well with experimental data. They provide a detailed understanding of the resistor with respect to EMP induced failures.

# MODELING OF FAILURE IN SEMICONDUCTORS DUE TO COMPLEX TRANSIENTS

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The failure levels of many semiconductor devices have been established by testing representative samples to high level rectangular pulses. This data has been used to determine the parameters in the thermal second breakdown (burnout) model for each device type. These models were then used to predict the failure of components in circuits subjected to induced EMP transients. This paper examines the assumptions made in employing a predictive failure model established from rectangular pulse data to the failure of devices to complex waveshapes and presents the results of a study to develop an analytical methodology for the prediction of semiconductor burnout for complex transients from test data obtained from rectangular pulse failure experiments.

Semiconductor burnout experiments were conducted on diode, transistor, JFET, MOSFET, and microcircuit devices for a variety of power pulse waveforms including single square pulses, bipolar damped sinusoids, as well as for a number of different bias conditions. The pulse width range investigated was from 3 nanoseconds to 300 microseconds. These experiments formed the data base for the identification and analytical modeling of the various device failure modes, and for the correlation between the various waveforms.

Preliminary conclusions of the study indicate that the device failure threshold levels due to various waveforms can, in general, be modeled and correlated with square wave data by use of the appropriate model. Certain exceptions and their impact are discussed in Dr. Kalab's paper.



Classification U

# ON THE NECESSARY AND SUFFICIENT CONDITIONS (THRESHOLDS) FOR DAMAGE OF SEMICONDUCTOR JUNCTIONS FROM ELECTRICAL TRANSIENTS

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Experiments are discussed which showed that a junction device (1N4148) whose condition for reverse failure was considered to conform to the presently accepted thermal damage models can exhibit "threshold" powers for failure differing by almost two orders of magnitude. Random samples of 10 devices from a controlled manufacturing lot were pulsed in the reverse direction with square pulses of 10μsec widht. A single pulse from a high impedance pulse source could damage the junctions involving a pulse power of only 2.5W. Applying full cycle square pulses of 10μsec half cycle width, the first half cycle forward biasing the junction, it was found that when the power of the forward biasing pulse was about 50-70 percent of that required for forward failure, the junction presented a very low impedance to the immediately following reverse biasing pulse and could dissipate, during this pulse, a power of 165W without degradation of the reverse breakdown voltage. The magnitude of the "power for failure", determined by the conventional method of step-stressing, was found to be 12.5W (with an error of approx. 30 percent). The implication of these effects for EMP vulnerability analyses is briefly discussed.

CLASSIFICATION U

HARDENING TECHNOLOGY SECTION

Session 3A

Thursday Afternoon 27 September 1973

Chairman: Byron Gage
Boeing Aerospace Company

# SYSTEM CONSIDERATIONS FOR EMP HARDENING

G. E. Morgan

Rockwell International Corp.

# Engineering Analysis of Cable Shields

by

E. F. Vance

Stanford Research Institute
Menlo Park, California

## ABSTRACT

A review of the current state of the art in cable shield analysis will be presented from an engineering viewpoint. The transfer impedance and transient responses of tubular shields will be used to introduce cable shielding analysis concepts. Comparisons of the computed and measured internal voltage waveforms will be given. This introductory material will be followed by a discussion of leaky shields, such as tape-wound and braided-wire shields. The concept of a transfer admittance to account for electric field penetration of the shield will be introduced, and engineering approximations to the transfer impedance and transfer admittance of braided wire shields will be given in terms of weave parameters. The variation of the transfer impedance and admittance with weave parameters will be described, and the analytical results will be compared with experimental data. Directional effects associated with electric and magnetic field penetration and those associated with dispersion will also be discussed.

5-3A-3

To Be Announced

HARDENING TECHNOLOGY SECTION

Session 3B

Thursday Afternoon 27 September 1973

**Chairman:** Byron Gage
Boeing Aerospace Co.

# CONNECTOR LEAKAGE INTO SHIELDED CABLE

by

Setsuo Dairiki

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## ABSTRACT

Connector leakage equivalent circuit model, its application to the design of the measuring equipment, and analysis of the results are developed to obtain parameters that describe leakage transfer impedance. Connector leakage transfer impedances in a fabricated multi-conductor shielded cable were obtained with a mating connector in which all the terminals are shorted together and coaxially connected to a 50 ohm input cable of a wide-band oscilloscope.

An equivalent circuit model for a junction of two concentric coaxial lines coupled by a small aperture forms the basis for a connector leakage model, where equivalent shunt current and series voltage sources represent connector leakage into a coaxial line from currents flowing on its exterior surface. Measurement data and interpretation based on the model indicate that the shunt current source may be ignored. The equivalent series voltage source has a component proportional to the derivative of the current flowing on the exterior of the coaxial line.

Pulse measurements offered a simple and a rapid method of determining connector leakage impedances. The rise time of the pulse generator was tailored to assure that the oscilloscope would exhibit the waveform of differentiated pulses without degradation while using a relatively low voltage pulse generator. Pulse generator connections to the cable consisted of two clamps straddling the connector joint to be measured. Pulse measurements on a fabricated cable system show multiple reflections from many cable branching and terminations. Nevertheless, connector leakage impedances are obtained easily from the observed waveforms by visually applying high pass and low pass filtering analysis to the waveforms.

# Transfer Characteristics of Power Service Transformers

by

Robert T. Bly, Jr.

Stanford Research Institute
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## Abstract

Laboratory tests of the transfer and transient response characteristics of five typical powerline service transformers and their normal protective circuitry (e.g., lightning arrestors -- three styles) show that the transformers can be roughly characterized as bandpass filters in the 10 kHz to 50 MHz frequency band, with a -6 dB "passband" extending from ~200 kHz to ~20 MHz. Although the test group included new and used transformers (made by three different manufacturers) of both 25 and 50 KVA ratings, CW transfer and pulse transient data obtained from them are quite similar, with variations in level that are typically less than two to one.

High-level drive tests show that the lightning arresters afford considerable protection. No damage to (or flashover within) the transformers has been observed for (primary-side) drive levels as high as 220 KV. The arrestors, which typically flashover (i.e., operate in their normal protective mode) at ~40 kV, also serve to limit the peak secondary output voltage observed (worst case was 25 kV across 100 $\Omega$). Removal of the arresters resulted in primary bushing flashover at ~100 kV. Efforts to simulate service drop EMP pickup by driving from the secondary side resulted in secondary bushing flashover at drive level of 40 kV. None of the tests appear to have inflicted any lasting damage to either transformers or arresters.

# EMP Penetration Through Imperfectly Conducting Gaskets in Hatches. Part I. Quasi-Static Solution

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The Dikewood Corporation
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## Abstract

A quasi-static solution technique is employed to determine the fields which penetrate an imperfectly conducting gasket surrounding a circular hatch in a conducting plane. According to the quasi-static approximations, the dimensions of the hatch and gasket are very small compared to the wavelength of the incident field. The current induced on the conducting gasket is considered as a new equivalent source for determining the penetrated fields. These penetrated fields are then used to define an overall shielding effectiveness parameter. Numerical results are presented for the penetrated fields at various positions in the region near the gasket, and an attempt is made to determine the position or positions where maximum penetrated fields occur. These quantities are calculated for several gasket dimensions and conductivities.

# TRIPLE BRAID CABLE MODEL

By John Palchefsky, Jr.
General Electric Company
Re-entry and Environmental Systems Division

Multi-layered braid is a popular shielding approach for cables where EMP protection must be flexible, lightweight, and workable. For one or two wavelength cables from one to 100 MHz, the method of braid termination strongly controls the attenuation of outer shield currents with respect to common mode currents on the inner core. The shield's attenuation can be modeled by a coupled set of transmission lines which are driven by sources at the termination joints. Different resonance patterns are detectable when the cable is installed in a laboratory test set and in a system. The model shows the resonance patterns to be a function of the loads formed at the cable connectors from pins to case. Further analysis shows that there are limitations to the removal of core resonances by impedance matching and that resistive terminations in the laboratory may even desensitize attenuation response to faults in the shield termination. In addition, the currents on the cores of branched cables exhibit sensitivity to the phases of currents on each branch.

This paper develops a triple braid cable model for a practical cable and shows how the model is exercised to relate the cable's laboratory test performance to its actual system performance. Data from laboratory and field tests are discussed and related to the model. Application of the modeling technique to a branched double braid cable is indicated.

5-3B-5

# The Effect of Weld Defects on RFI Shielding Effectiveness

by

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Construction Engineering Research Laboratory

To date many specifications for electromagnetically shielded facilities have required that weld seams be 100% defect-free although almost no data is available to support this. Such high levels of quality control are expensive and time consuming. An investigation was performed to determine the effect of weld defects on the shielding effectiveness of shielded enclosures containing welded seams. More specifically, the amount of shielding degradation as a function of type and size of weld defects in Electromagnetic Pulse (EMP) shielded enclosures was desired for RFI frequencies of 10 KHZ to 10 GHZ.

Defects were intentionally implanted in welded 11-gage steel panels. The panels were then tested in a high quality RFI-sealed shielded enclosure to ascertain the RFI attenuation characteristics of the defect.

Preliminary results of this investigation have shown that weld seams need not be 100% defect-free to afford adequate shielding effectiveness as is now required. Indeed, many harmless defects, with respect to shielding effectiveness, may now be precipitating expensive and time consuming weld repairs unnecessarily. Corresponding to the possible relaxation of the present strict weld quality requirements, this investigation indicated that there is some defect size level at which the shielding effectiveness characteristics of the weld seam become critical. More data is needed to quantitatively define these levels.

5-3B-6

W. A. Robinson
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# EMP Shielding by a Steel Liner

The EMP protection of many systems is furnished in part by a shielded enclosure of steel. For the case of shielding against large current densities lasting for times of milliseconds, the saturation of the magnetic properties becomes the dominant influence in the shielding.

Numerical solutions of the magnetic field penetrating steel have been obtained using a one-dimensional nonlinear diffusion equation. The Rayleigh and the Froelich-Kennelly relations are used to approximate the actual magnitization curves of the steels. The results show the fields inside the shielded region are particularly sensitive to the late time behavior of the external fields and the peaks in the internal fields can occur significantly later than the end of the external signal.

# "Transmission of Electromagnetic Waves Through a Pair of Parallel Wire Grids Including the Rectangular Mesh Limit"

by

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The motivation for the study was to establish the validity of representing a finitely-conducting wire mesh screen by an equivalent thin homogeneous sheet. To this end, we formulated the boundary value problem of two non-intersecting grids (whose wires were mutually perpendicular) for a plane wave at arbitrary incidence. The separation between the two grids was allowed to vanish in order to characterize the wire mesh limit. The coupled set of equations were solved numerically by matrix inversion and by a perturbation scheme. The results indicated that the transmitted waves were elliptically polarized for oblique incidence, but in certain limiting cases the depolarization vanishes.

Abstract for AFWL Joint Electromagnetic Pulse Technical Meeting, 25-27 September 1973,

# Time-Domain Computer Models of Thin-Wire Antennas and Scatterers*

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The transient responses of various thin-wire antennas and scatterers have been studied through the numerical solution of a time-dependent electric field integral equation. The solution is set up as an initial value problem and proceeds via time stepping. This is a generally more efficient approach for determining the transient response of wire objects than frequency domain solutions which are Fourier transformed to obtain transient characteristics. The time-domain solutions have been verified by comparisons with other solutions for structures such as the linear dipole, circular ring, conical spiral, and V-dipole. In addition to providing wide-band frequency domain information via Fourier transformation, the time-domain solutions permit the temporal development of the currents and charges to be followed, which permits ready demonstration of reflections from junctions or ends of wires, the effects of loading, phase dispersion of the current waves as they travel along the structure, and structure resonances.

The characteristics of several other structures is considered in addition to those above, with the aim of providing insight into their EMP response characteristics. Attention is devoted to methods of data presentation which efficiently ultilize the large amount of information which the time domain solution yields and to exploiting this data for problems of practical interest. These studies show, for example, that a current saturation occurs when a long wire (in free space) is illuminated by a short pulse plane wave. Insight gathered from the time-domain solution of this problem has lead to a simple method of estimating the maximum current on the wire.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

# SOME COMPARATIVE NUMERICAL COMPUTATIONS ON WIRE SCATTERS

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Numerous persons have reported studies of thin wire antennas and scatterers, and typically, such analyses are based upon numerical solutions of integral equations of either the Pocklington (E field) or Hallén (magnetic vector - electric scalar potential) type. Various basis sets have been used for representation of the wire current, the unknown to be determined in either type integral equation. The particular basis set employed in a given case usually is selected to favor one, or a weighted combination, of the following: Capacity to represent well the unknown current, amenability to attendant numerical calculations, and readiness of convergence to solutions. Presented in this paper is an investigation of the use of the two types of equations mentioned above in conjunction with several selected bases to emphasize the efficiency of numerical solutions. Efficiencies of these solution techniques/basis sets are delineated, and the claims of the authors are supported by voluminous data showing current distributions on straight and L-wire scatterers. Deficiencies are discussed in detail and schemes for overcoming them are presented. Finally, a very close relationship between Pocklington and Hallén equations is pointed out and a solution technique embodying desired features of each if described.

HARDENING TECHNOLOGY SECTION

Session C-1B

Thursday Afternoon 27 September 1973

Chairman: D. Merewether
Mission Research Corporation

ABSTRACT

# ATTENUATION OF EMP/IEMP PULSE EFFECTS THROUGH LOW-DENSITY MATERIALS WITH HIGH ELECTRICAL CONDUCTIVITY

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McDonnell Douglas Astronautics Company

A technique to markedly diminish electromagnetic (EMP) fields using a low-density material with high electrical conductivity was developed and tested. A thin, cylindrical cavity (pillbox) was current pulse injected, and the pulse magnetic field produced is measured by Moebius loops. The pillbox was then filled with a low-density aluminum material with an insulator separating it from the cavity walls. The test was repeated showing a greater than 40:1 reduction in fields just 2-5/8 inches from the injection line. The test was repeated with a faster pulse, showing an even larger attenuation factor (100:1) in accord with theory. The test was repeated with the foam in good electrical contact with the cavity walls, and no measurable magnetic field is observed. The observed pulser noise level was on the order of $10^{-6}$ of the injection level.

The tests (empty cavity, foam insulated from wall, and foam in electrical contact with the wall) were repeated using the FX-25 flash x-ray machine at MDAC. Substantially the same reductions were seen in laboratory current injection tests. The mechanism underlying the suggested field reduction technique was verified, and studies to determine how this technique could be utilized in various systems were conducted.

This paper is recommended for presentation as a part of technical area e (Hardening Technology) and will be classified Confidential.

# SYSTEM LEVEL CONSIDERATIONS SECTION

SYSTEM LEVEL CONSIDERATIONS SECTION

Session 1

Tuesday Afternoon 25 September 1973

Chairman: Dr. William R. Graham, Jr.
R&D Associates

# EMP AND NAVAL SYSTEMS

N. Taslitt and E. Rathbun

Naval Ordnance Lab

6-1-2

# ON A SYSTEM REPRESENTATION FOR WELL-POSED IDENTIFICATION

## ABSTRACT

An input/output representation (the $\lambda$-representation) for linear, time-invariant systems is discussed. The identification of this representation is mathematically well-posed in many cases. Thus its determination is often relatively insensitive to certain experimental uncertainties. Quite generally rational error-in-identification bounds can be found. The ill-posedness of impulse response identification is demonstrated, thus enhancing the usefulness of the $\lambda$-representation as an alternate model for physical systems which can only be determined by experiment or from input/output records. Among the practical considerations investigated are the effect of input and output uncertainties (noise) in the identification experiment, and the treatment of the case when only discrete data are available. The problem of finding minimal realizations and the interpretation of this method relative to other methods are discussed. Finally, the application of this representation is considered in EMP threat prediction with hard error bounds provided on the predicted threat. For this particular problem the applicable case of the $\lambda$-representation turns out to be what is classically known as the ramp response representation.

# THE COMPONENT CONNECTION MODEL IN SYSTEMS IDENTIFICATION, ANALYSIS AND DESIGN

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## ABSTRACT

This paper presents a recently developed mathematical systems model which has impact on computer aided design and analysis techniques. This impact comes about via the computational efficiency allowed by the model structure. The model is structured so connection information is purely algebraic in the variables of dynamical components. It appears that this model structure will lead to new identification techniques which will be particularly applicable to integrated circuitry. Uses of the model in fault isolation and trending techniques are also included.

David S. Becker

GTE Sylvania Communication Systems Division

ABSTRACT: A STRATEGY FOR LARGE EMP MODEL ANALYSIS

In analyzing the effects of EMP on a large physical system, it is often necessary to model the system in terms of large numbers of electrical network elements. The number of elements required may well be larger than the capacity of any available computer network simulation program, so that the problem must be divided into smaller parts and solved in some sequential manner.

The problem is made even more difficult if non-linear elements are present in the model, if distributed excitations are present on cables, or if "feedback loops" exist within the circuit diagram. It may also be a consideration that more than one environment (i.e., set of driving sources) is to be applied to the model, and it is thus desirable to minimize redundant computation where possible.

This paper describes an analysis strategy which GTE Sylvania has evolved in its EMP studies of very large systems. The strategy presupposes the availability of a set of typical software packages for transient, frequency domain, transmission line and other network simulation tasks. Rules for efficient division of the network into partitions are given, and a convolution technique for integrating nonlinearities into an overall calculation is described. Alternate methods for incorporating distributed excitations along cables are also provided. These principles allow the setting up of a series of calculations to obtain the desired results with a minimum of computation.

# A SIMPLIFIED APPROACH FOR VERIFYING THE EMP HARDNESS OF EXTENSIVE, HARDENED, GROUND FACILITIES

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Present day sensitive equipments are susceptible to upset and/or damage by EMP pulse energy, either conducted to the equipments on interconnecting hardwire circuitry or by direct induction from the incident fields. Effective protection of the sensitive equipments can be achieved by shielding of the equipments and interconnecting circuits, and through use of isolation devices (e.g., filters and Faraday shielded transformers) to reduce conducted transients. Large ground based installations have been designed to incorporate these types of EMP protection.

This paper addresses the task of providing an EMP hardness verification for an extremely large and complex ground based installation. The basic approach which is presented utilizes successively increasing detail on areas of remaining uncertainity; an approach which provides economical, timely verification of portions of the system that exhibit hardness by a large margin. The initial analytic effort surveys and ranks all of the components of the system and screens out for additional study those which are potentially susceptible to EMP transients (either conducted or field). In order to further reduce the amount of analytic effort, the paper describes how functional sub-systems are grouped so as to take advantage of similarities and redundancies within groups.

EMP flow-paths within each group are then identified for theoretical analysis. At each step of the hardness verification, conservative judgments and error bands introduced so as to minimize the overall effort. If under, such conservative analysis hardness verification cannot be achieved, the analysis is reiterated using more detailed and less conservative methods. It is shown how the analytic results lead to test recommendations and how the test results may be folded back into the hardness verification process.

* This work was supported by the U. S. Army Corps of Engineers, Huntsville Division, Huntsville, Alabama, Contract DACA87-72-C-0002.

Serge Stepanoff

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ABSTRACT

TACFIRE System EMP Analysis

The methodology of the EMP survivability - vulnerability analysis of the TACFIRE System is presented.

The TACFIRE System consists of data processing hardware, software, and associated data entry, display, and control devices that are necessary to automate the Field Artillery functions selected by the Army.

The system physically consists of man-transportable equipments in environmental aluminum "transit cases", and associated cabling and power sources. It is capable of being configured in a variety of ways, including being mounted in a shelter, or in the open as in a tent or a cave.

The analysis attempts to take into account the various unique EMP related problems posed by this highly mobile tactical data processing system.

An overview of the analytical and computer techniques used to predict the following is given:

1. Penetration of the equipment cases by EMP energy and subsequent induction onto internal wiring.
2. Induction of transients onto system cabling.
3. Effects of the EMP induced transients on circuits.
4. Special problem areas, i.e., antennas and equipment case apertures are treated.

The result of the analysis is a system vulnerability assessment and recommendations for EMP hardening.

# MODELING THE EMP EXCITATION OF A COMPLEX POWER SYSTEM*

Dennis R. Bernotski
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Transmission line theory is applied to the problem of modeling the EMP excitation of the Power System of a Minuteman Launch Facility. The use of Thevenin equivalent circuits for the overhead powerlines for both common and differential mode with plane wave excitation is presented. Computer comparisons between the excitation of common and differential mode voltages are shown for various angles of incidence and for both vertical and horizontal polarization.

The method used for modeling the load impedances at the main power distribution panel is presented along with impedance measurements from typical launch facilities. The overall quality of the model of the power system for a Wing I Launch Facility is verified by using measured data taken at the site with the Horizontal RES Antenna.

* This work was supported by the Space and Military Systems Organization, Norton Air Force Base, San Bernadino, CA. Contract F04701-72-C-0210.

# THE DIRECT DETERMINATION OF $C^3$ NODE VULNERABILITY

Guillermo B. Lamers
Alfred G. Brandstein
David A. Finley
Egon Marx
John C. Ingram
Thomas A. Tumolillo

A new and more valid definition of vulnerability for $C^3$ systems is derived and displayed. Traditional EMP testing procedures only allow the computation of this quantity by indirect, ill defined and rather complex algorithms. As a result, HDL has designed and constructed an instrument to directly measure the mecessary parameters for the determination of vulnerability. The theory and construction of this instrument, the communication Monitor and Control System (CMCS), will be described. In addition, the interrelation between the CMCS' CONNSEPT simulators will be exhibited.

CLASSIFICATION: Unclassified

# 'IN FORMATIC' AS A VULNERABILITY ASSESSMENT/PREDICTION TOOL IN $C^3$ - SYSTEMS: THE PREMPT DATA BANK (PDB)

Guillermo B. Lamers
Alfred G. Brandstein
Thomas A. Tumolillo
David A. Finley

This paper describes a hierarchical set of multi-level EMP Data Banks, designed and implemented by HDL to provide instantaneous, low overhead, arbitrarily complex, and arbitrary order cross-correlations between observed vulnerabilities and stored electromagnetic and functional response data. The architecture of the system is set up as to allow for dynamic restructuring of data sets by means of total interaction with application software, CONNSEPT simulation, and specially designed hardware monitoring systems (CMCS).

Due to general purpose algorithms, the PDB is a useful tool for the definition of minimum essential factor spaces for $C^3$-node vulnerability surfaces. The PDB will be discussed, and sample results will be displayed.

CLASSIFICATION (U)

# $C^3$ NODE/NETWORK SIMULATION IN AN EMP ENVIRONMENT

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This paper is concerned with the predictions on AUTOVON NODE/NETWORK performance, as derived from general purpose stochastic simulation models. The pertinent computer codes were developed, validated, and exercised by the U.S. Army Harry Diamond Laboratories. The computer codes are capable of simulating the 'true-to-life' functioning of the network and the individual nodes, to arbitrary level of detail, both under normally operating, as well as under the most general stressed conditions. The network stresses which are accounted for in the models fall into two broad classes: (a) independent performance degradation, which may range from selective functional misbehavior to catastrophic failure, for any (or all) nodes, functional and/or hardware components of nodes, or node complexes, within the network. (b) Sudden, localized, and/or distributed surges in the traffic level with arbitrary priority profile.

The codes allow for detailed tracing of individual calls through the normally functioning or stressed network, as well as for the calculations of detailed traffic statistics at any or all sets of functional and/or hardware component within the system. In view of their generality, the codes are also useful for hardware/software optimization studies. Results of sample runs will be displayed and discussed.

CLASSIFICATION (U)

# FACILITY RESPONSE PREDICTION CODE

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The Facility Response Prediction Code, FRESCO, is being developed for the analysis of EMP interaction with and coupling into large electronic systems. The work is sponsored by DNA for the joint DNA/DCA Program for EMP Testing (PREMPT). The code is an extension and generalization of that developed and used on the Minuteman In-place program. The code, FRESCO, is modular, expandable and user oriented; code modules for Environment, Penetration Coupling Paths, Critical Components, and Functional Response can be run either singly or together for system analysis.

Many other computer procedures have been developed for portions of the EMP system analysis task. These codes usually have shortcomings either in the size of network, system, or circuit analyzed or in the level of detail available in the solutions. FRESCO contains nested and linked job steps, or code modules, so that the calculated output of one module can provide both data and program control to succeeding programs. This type of linked coding has evolved at Boeing to the present code. Elements of the code are an Executive code, the Automated Assessment System (AAS); Numerical Analysis procedures, frequency domain transfer functions (TRAFFIC); time domain (CIRCUS); and Fourier Transform (FFT); and a Supporting Library of subroutines for special purpose calculation. Specific systems are analyzed by means of model libraries that contain the physical and geometric descriptions.

This paper provides the detailed discussion of the code organization and library contents.

* Supported by Defense Nuclear Agency, Contract DNA-001-72-C-0236.

6-1-12

# ELECTRICAL MODELING OF EMP INTERACTION WITH AUTOVON SWITCHING CENTERS

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Analytical procedures have been developed to analyze EMP interaction with communication facilities. The predicted coupling to cabling and exposed wires are direct application of antenna and transmission line theories. The resulting analyses* are combined into a computer code FRESCO which has been used to calculate the EMP response of the Polk City AUTOVON Switch.

Based on an electrical analog for EMP coupling into facility cables, code is developed for the penetration paths from the penetrations to circuit components within equipment racks. The parameters of the analog include cable orientation with respect to major sources, cable interconnections, shielding, equivalent transmission line impedances, and terminating loads. The core wires contained within the cables, are analyzed by means of the Boeing developed TRAFFIC program which is capable of solving large linear networks.

Parallel to the analytical effort, an experimental program using the Transportable EMP Simulator (TEMPS) is supported by DNA/DCA to determine AUTOVON hardness. The results obtained from TEMPS measurements compare favorably to analytical results.

* Supported by Defense Nuclear Agency, Contract DNA-001-72-C-0236.

# FUNCTIONAL RESPONSE PREDICTION*

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A functional analysis, coupled with the predicted electrical response of the Polk City, Florida, AUTOVON Switch, has been used to determine the functional response of the system. Parameters, which describe the performance of the system have been identified and calculated.

A functional analysis was made to identify components which are critical to switch operation. Margins-of-safety to damage and upset of representative samples of these components were calculated using computer code with component electrical threshold values for damage and upset entered as parameters. Those components which had small or negative margins-of-safety were further analyzed to predict an average probability of upset or damage. The types of service provided by the switch were analyzed and the functional response to damage or upset was determined for each type of service. The response of the facility can be described in terms of the probability and duration of the occurrence of specific types of malfunction.

The paper contains a description of the procedures which were used to calculate the probabilities of damage and upset and also discusses the Polk City AUTOVON functional analysis and the method of calculation of the response parameters.

* This work was sponsored by Defense Nuclear Agency, Contract DNA001-72-C-0236.

# RES I TEST OF A MINUTEMAN LAUNCH FACILITY*

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This paper describes the RES I test at Wing IV, LF E-09 conducted between 28 August and 21 September 1972. The helicopter borne vertical and horizontal polarized simulators illuminated the site from two ranges, three elevation angles and eleven azimuths. The resulting signals were measured on the power lines leading into the site, on test points inside the buried Launch Support Building and on penetrations and critical circuits inside the Launcher.

The assessment of the Minuteman WS133-AM Launch Facilities is dependent upon a knowledge of the azimuthal, and elevation angle dependence of the system response as well as the variations in this response that result from different polarizations in the incident EMP. Assessment is also dependent upon the development of a model of the Launch Facility that is capable of producing the measured responses so that system responses in hostile environments not amenable to test simulation can be predicted.

The specific objectives of the test were:

a. To determine the directional and polarization dependence of the response of the Launch Facility, excluding any contributions produced by power line pickup.
b. To determine the directional and polarization dependence of the response of the power line pickup.
c. To determine the relative level of the power line coupling into the Launch Facility.
d. To determine the relative level of the launcher closure penetration during the Terminal Count Down (TCD) mode when the closure is open and the upper umbilical is still connected.
e. To obtain data to verify the E-09 power line models and the power network coupling to other penetrations in the LSB.

The paper will present the rationale behind the selection of the specific test points, the azimuthal and elevation angles, and the ranges. Typical reference and down hole signals will be shown with comments on repeatability and frequency content.

* This work was supported by the Space and Military Systems Organization, Norton Air Force Base, San Bernadino, CA. Contract F04701-72-C-0210.

6-1-15

# EMP HARDNESS QUALITY ASSURANCE TESTS

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This paper discusses techniques that can be employed to assure that EMP hardness, designed into weapon system elements, is maintained through hardware fabrication, assembly, acceptance test, and installation in a typical manufacturing and field installation cycle. Included in the discussion are evaluation tests, qualification tests, quality assurance acceptance tests, and system installation tests.

Evaluation tests are conducted to determine the most economical means of solving the technical problem--essentially value engineering. These tests for some items may include extensive pulse and insertion loss tests while others would involve only simple insertion loss measurements.

Qualification tests demonstrate that the production article meets all the requirements of the equipment specification. The tests, in general, require direct signal injection for determination of insertion loss and assurance of no circuit impact or damage. Injected signals can be high or low voltage damped sinusoids, double exponential pulses, or CW, in ranges from 10 Hz to 100 MHz.

Quality assurance tests may be performed on a sampling basis to provide confidence that hardness requirements are not compromised in the course of manufacture of the production articles and are usually limited to low-voltage direct-drive pulses and CW insertion loss tests, principally to provide assurance of hardness similarity between identical units.

System tests provide assurance that essential EMP hardness features of the installed system are not compromised as a result of workmanship during installation. Signals are injected into selected drive points and resulting signals at selected receive points are measured to verify that insertion losses provided by system filters and cable routing are satisfactory. Signals are less than 500v RMS CW in the range 10 kHz to 50 MHz, and usually are limited to 5 - 10 frequencies injected sequentially.

This work was performed under Minuteman Contract F04701-72-C-210D.

6-1-16

William C. Hart

Mission Research Corporation

# THE HISTORY AND STATUS OF EMP DOCUMENTATION AS RELATED TO SYSTEMS WORK

The history of EMP documentation is traced to early test reports by Haas, Malik, Wimentz and others. Later theoretical work of about 1958-1962 is summarized including Russian (Kompaneets), British (Popham, Taylor, et al), French (DeLloue), and United States (Bethe, Longmire, Karzas, Latter, Suydam and others). The first organized attempt to document EMP research is described -- the 1964 summer working groups at SRI and GE TEMPO. The results of documentation efforts in the late 1960's are reviewed. These include the first edition of the DNA EMP Handbook; the beginning of the AFWL EMP note series; the conception and development of the EMP course; the EMP computer code survey; the SRI data tapes; early attempts at EMP movies; the LEMP 1 library; the AFWL tech file; symposium proceedings, etc.

The effect of the past work in EMP documentation on systems interaction work is discussed and the current status of EMP documentation and information sources is outlined including: the note series; EMP handbooks (the In Flight handbook, Environment Handbook, IEMP Handbook, SGEMP Handbook); movies; the EMP course and seminars; the open literature; and systems technology reports. Future needs are reviewed and recommendations made for improvement of systems EMP documentation programs.

SYSTEM LEVEL CONSIDERATIONS SECTION

Session 2

Thursday Morning 27 September 1973

Chairman: Maj Williams Adams
Defense Nuclear Agency

# CONTINUOUS MONITORING OF EMP SENSITIVITY OF SYSTEMS

by

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This paper deals with the need for hardness assurance in EMP hardening of systems. Discusses some proceedures which can be used to implement EMP hardness assurance. Describes a Shielding Integrity Monitoring System and its application for continuous monitoring of the EMP hardening level of a system. The Shielding Integrity Monitoring System consists of a transmitter which drives a shielded system externally and internal receivers which monitor the transmitted signal levels and provide an indication of EMP sensitivity of the system.

# B-1 EMP EVALUATION MODEL

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Rockwell International Corp.

To assure that EMP hardness of the B-1 Aircraft is achieved, it was essential to begin an evaluation early in the system development. This will greatly aid in identifying what data is missing, where the data is uncertain, and what work needs to be done in the future.

Skin current responses, point-of-entry transfer functions and cable responses for the B-1 have, in many cases (references included), been predicted individually. A combinative model which can tie the pieces together and synthesize an overall prediction was required.

Esixting modeling techniques were unacceptable for a number of reasons. Existing techniques required a very large amount of data processing time and the associated expense. They are not amenable to large numbers of runs required to incorporate design changes, parameter changes, new and superior data, or parametric investigations.

The selected model approach utilizes a transfer function approach to EMP analysis. A system model can be envisioned as a large collection of transfer functions and a topology involving serial and parallel paths that connect them together. This paper will describe the details of this approach.

This work was performed under contract F29601-72-C-0037 for the Air Force Weapons Laboratory.

# ELECTROMAGNETIC SYSTEMS MODELING

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Maxwell's equations describing electromagnetic systems are linear. This enables one to construct a model of an electromagnetic system having certain properties at a given wave length, which will have the same properties at another wave length provided all linear dimensions are scaled appropriately. In his classic paper[1)], Sinclair had derived conditions which an electromagnetic system model should satisfy either to be a practical absolute model (quantitative) or to be a practical geometrical model (qualitative). He arrived at these results by making use of fundamental units, Maxwell's equations and some physical facts.

This paper shows that Sinclair's results can simply be obtained by realizing the relativistic covariance of Maxwell's equations which manifests the facts that (1) space and time are on the same footing and occur as a four-vector $X_\mu$, (2) and electric and magnetic fields are parts of the single six component antisymmetric field strength tensor $F_{\mu\nu}$. The theoretical and physical limitations of simulating systems by scale modeling are considered. A brief analysis of why measurements of some quantities (e.g. radiation pattern) are more reliable than the measurements of some other quantities [e.g. impedance] for the above models is given. Finally, the influences of non-linearities of systems on the simulation models and measurements are considered.

The effects of using scale models for analyzing systems for electromagnetic pulse vulnerability, survivability and hardening are considered and the relative advantages and disadvantages of this type of approach are also discussed. The scale model approach becomes very necessary for EMP studies of large systems such as very low frequency transmitter/receiver stations which may spread out over 1,000 square miles. The scale model approach can also be used to simulate electromagnetic pulse, say due to a high altitude burst, with high frequencies, arbitrary polarization and angles of arrival; information such as these has been useful in determining worst case conditions and in validating analyses.

[1)] G. Sinclair, Proc. I.R.E. 36, 1364 (1948)

6-2-4

by Chris Ashley, AFWL.

Unclassified.

## Abstract

## Effects of Prior Knowledge on Bayesian Implications of Experimental Data

EMP System Design and Assessment Notes 2, 3, 12, and 14 discuss calculation of confidence in system reliability from experimental data. Those notes all assumed that information concerning what fraction of the population was "good" was available from no other source than sampling a subset of the population. Formulas were derived for confidence that the fraction was within a specified interval given the size of the sample subset, the fraction of the subset which was found to be "good", and minimal information about the structure of the population and how the sample subset was selected from the population.

However, sometimes information about population reliability may be available from sources other than just this kind of data. Such additional information can be combined with the information from experiment to yield improved calculations of confidence in system reliability. The purpose of this paper is to present a way of doing this. Specific examples are worked out to illustrate the consequences for interpretation of test results. As one of the examples, numerical results are presented showing how prior knowledge affects the amount of uniformly successful testing required in order to attain a given confidence in a given reliability.

# The Sandia Laboratories/AFWL In-Flight EMP Handbook

J. A. Cooper

Sandia Laboratories

## Abstract

Sandia Laboratories has recently published, with AFWL support, an in-flight EMP Handbook. The handbook provides analytic data on various electromagnetic pulse effects (mostly in parametric and normalized form), hardening and circumvention information, and material on instrumentation and test techniques.

For analysis, EMP response can generally be broken down into four basic factors, and each provides a topic for a chapter in the book. These are: 1) the response of a missile or aircraft as an antenna or scattering structure, which results in exciting currents flowing on the metal skin; 2) the antenna response of holes, cracks, cables and connectors mounted on the aircraft or missile, which allows energy to penetrate to the vehicle interior; 3) coupling of signals within cables and packages, which allows energy to be transmitted to sensitive electronic circuits; and 4) the response of the electronics to these signals, which may result in electronic "upset" or component damage.

In this paper, the content of the EMP Handbook is described, and an example problem is pursued in order to illustrate the utility of the information.

6-2-6

# TECHNIQUE FOR DERIVING EMP SPECIFICATIONS FOR AERONAUTICAL SYSTEMS

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The design of EMP hardened weapons systems requires eatablishing EMP performance specifications. The specifications apportion the system hardness to individual hardening levels (e.g., shields, filters, limiters, etc.). An obvious trade exists between the degree of protection versus functional parameters such as cost, weight, reliability, etc. Even when this takeoff is made and the target hardness level is established, the individual specifications can be selected to achieve a functionally optimized hardened design. This paper presents an approach to obtaining an optimum set of EMP hardening specifications for a given aeronautical weapons system.

Two types of specifications are treated. The first for uncontrolled parameters. These are parameters whose values are fixed by weapons system design for which it is not feasible to impose controls in order to assure EMP hardness. The most important of these parameters is the coupling to exposed cables. These parameters are estimated experimentally and statistical techniques are used to develop a specification with a given confidence level.

The second type of specification applies to parameters that can be readily controlled to achieve a given EMP hardness level. These include the protection characteristics of shields, filters and limiters, and circuit failure thresholds. For a given set of functional requirements, these controlled parameters can be traded to optimize a functional requirement (e.g., cost, weight, etc.). An example is provided to show the application of the methodology to a simplified weapon system.

This work was supported by the Air Force Weapons Laboratory, Kirtland AFB, Albuquerque, New Mexico, Contract F29601-72-C-0028.

# DEVELOPMENT OF AN EMP SPECIFICATION FOR AERONAUTICAL WEAPON SYSTEMS

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Specifications for all new weapon systems require that the system continue to satisfy mission completion requirements after exposure to a specified nuclear electromagnetic pulse. This paper presents a concept for the development of cost effective protection design specifications for the electrical/electronic (E/E) equipment used in the weapon system. The preliminary results of applying this concept to the specification development of a representative aeronautical weapon system are included.

A two-tier approach is utilized to achieve the following: a) characterize the interior EMP environment incident on E/E equipment, b) assess the EMP susceptibility of E/E equipment, c) define the EMP protection designs required to reduce the incident environment to levels equal to or less than the susceptibility levels, and d) verify by analyses and tests that the designed protection has been achieved.

The first tier effort, resulting in preliminary EMP E/E equipment design specifications, is conducted before detailed designs are available in order to establish a baseline for the program organizations to use as a common design goal. These preliminary specifications result basically from a trade-off of two parameters: a) preliminary estimates of time histories of the EMP-induced voltage, current and power levels at the E/E equipment terminals; and b) preliminary estimates, based on the design data in hand at the time, of the failure thresholds of the critical components (transistors, diodes, integrated circuits) within the E/E equipment. The resultant preliminary specifications were those levels just below that which would severely impact E/E equipment designs and still be achievable with fuselage and/or cable shield designs.

The second tier effort as the design matures, includes detailed EMP coupling analyses and full scale model tests in an EMP simulator to: a) verify that the specified levels at the E/E equipment terminals will not be exceeded; b) identify the need for, and recommend specific additional shielding to the fuselage and/or cables to limit the EMP-induced transients to a level below the specified values; and c) verify the EMP environment determined by analysis.

This work was performed under Contract F33657-72-C-0923-1.

# TACAMO ELECTROMAGNETIC PULSE (EMP) PROGRAM

by

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ABSTRACT: The TACAMO aircraft is a C-130 outfitted to provide a very low frequency (VLF) communication link between land-based and sea-based communication systems. The aircraft employs long trailing wires to perform this function in addition to solid-state message processing equipment. The TACAMO EMP program has been established to evaluate mission performance in an EMP environment, to harden the system as required, and to verify the hardness.

Flight tests using the Naval Ordnance Laboratory's Electromagnetic Pulse Radiation Environment Simulator for Ships (NOL's EMPRESS) Facility and the Air Force Weapons Laboratory's (AFWL) helicopter-supported horizontal Radiating Electromagnetic Pulse Simulator (RES) have been completed and the program thus far has progressed to the analysis of this data. The TACAMO aircraft was also tested briefly in the AFWL Vertical Polarized Dipole (VPD) Facility.

This paper presents the methods and results for these low level coupling tests.



Noel T. Poplco

CLASSIFICATION: Unclassified

# ELECTROMAGNETIC PULSE (EMP) DATA MANAGEMENT

by

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ABSTRACT: The importance of efficient and accurate data management in EMP testing will be discussed. Data management includes the verification, reduction, and processing of all data taken during the testing program including both free field inputs as well as system configuration and response. Specific applications to the TACAMO aircraft test will be discussed. Computer codes have been developed to assist in the data management function and these will be presented. The application of these codes to the different simulators used in this program will be shown.



Noel T. Poplis

CLASSIFICATION: Unclassified

Mitchell A. Skinner
Air Force Weapons Laboratory

# An Organized, Six Step Approach to System EMP Vulnerability Assessment

To ensure an organized approach the EMP vulnerability assessment of a deployed system, a method of six steps has been developed that yields a quantitative assessment of the deployed force survivability.

The six steps used in this assessment approach are:

1. Identification of system critical equipment,
2. Identification of mission critical circuits in each critical equipment,
3. Construction of an Assessment Matrix to identify available data,
4. Extrapolation of sub-threat level test data to threat-level,
5. Calculation of individual, system probability of survival curves, and
6. Determination of force survivability from individual system survivabilities.

The details of these six steps with an application to a strategic missile system are explained in this report.

6-2-11

M.A. Skinner
AF Weapons Laboratory

# Determination of System Probability of Failure from Subsystem Probabilities of Failure

This note presents a method for determining a system probability of failure when the probabilities of failure of individual subsystems are known. The note shows how to obtain upper and lower bounds on the system probability of failure when the means by which subsystem failures combine to produce a system failure are not known. The note also develops a "nominal" probability of failure for the case where the individual subsystems operate independently to produce a system failure.

6-2-12

# PRODUCTION HARDNESS ASSURANCE IN MINUTEMAN

by

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The procedures and techniques for controlling the hardness features of weapons system improvements through the manufacturing, assembly, and installation phases of development are presented. The hardness assurance program is based upon the utilization of existing controls to prevent degradation of hardness wherever possible. Through a systematic review of details of equipment design and production techniques, the relative importance of a particular feature to hardness is determined and the effectiveness of existing production controls is evaluated. Where existing quality control and other manufacturing controls are found to be inadequate, they are either modified or new procedures are developed. The new and modified procedures considered include training, process controls, parts screening, tests and measurements.

ABSTRACT

# AUTOPILOT EMP SUSCEPTIBILITY EVALUATION

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MDAC is nearing the completion of a major nuclear vulnerability and hardening program which has been underway for the last four years. One phase of this program has involved an investigation of the Spartan autopilot's susceptibility to EMP effects. This paper will present test and analysis techniques and simulation hardware which were used to assess the susceptibility of subsystem blackboxes. While the work was performed for a specific EMP waveform and blackbox subsystem, the basic hardware and techniques can be used in determining blackbox susceptibility to general transient currents (e.g., EMP, REMP, IEMP). Testing of the autopilot demonstrated the inadequacy of present circuit analysis techniques, in the area of EMP response, which addresses interface circuits only. Standard techniques do not employ high frequency models of components, nor do they consider the fact the energy may be delivered to buried components by electromagnetic coupling rather than conduction. The test results show that buried circuits can be more susceptible than interface circuits. As a result, an alternate method for analyzing burnout susceptibility will be given. Topics to be covered include the following:

1. The role of analysis in a susceptibility test program.
2. Investigative testing to supplement failure level testing.
3. Selection of critical components and circuits for evaluation.
4. Development of cable to component coupling models for high frequencies.
5. High level transient generation equipment and techniques for upset and burnout testing on active units.
6. Confidence levels in susceptibility test results.

This paper should be included in technical area d (Testing Techniques), and will be unclassified.

# Hardening the System

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The primary EMP effort at the system level is to determine what the worst-case forcing functions look like at the subsystem interfaces. These are the inputs to the designers who must provide adequate protection, compatible with the functional requirements of the system.

Two classical examples cover most of the practical cases of transverse field induced forcing functions: coupling through long cables, and coupling of the carrier body inducing a forcing function in the internal circuitry. Idealized forcing functions (e.g., EFF) and practical testing forcing functions diverge in their time history, but the overall effort satisfies the requirements, and usually provides an excellent verification of system hardness.

The overall engineering concept of the cable/circuit reaction to the outside environment is defined and the most relevant features brought to the attention of designers so as to limit their hardening efforts to realistic requirements. The impact of such concepts upon testing plans and procedures is discussed for long and short cable runs suspended above, layed on and buried in the ground. Parallel considerations are discussed for aircraft, missiles, and terrestrial carriers responses. Testing approaches are presented which determine the resonances of the carrier. The actual testing of subsystems with injection devices is described and the recommended instrumentation detailed.

Unclassified data is presented to show present achievements of our laboratories.

# MODELING OF THE GRC-106 RECEIVER FOR EMP ANALYSIS*

by:

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The RF amplifier and first mixer of the GRC-106 receiver were modeled for the purpose of a computer simulation of the behavior of this receiver when subjected to antenna coupled EMP. The antenna was modeled using a lumped parameter network (LPN) model.

Two major difficulties arose in the computer simulation of the receiver. These are: obtaining adequate information to model the receiver circuits, and the long running times on SCEPTRE for the simulation. In the first case, the information provided in Technical Manuals is inadequate to accurately model the circuit, since such information as self and mutual inductances, inductor Q's, filter circuits, and crystal parameters are frequently missing. The long running times on SCEPTRE are the result of the program following the ringing frequencies in the tuned circuits. For an RF stage tuned to 30 MHz, this may require SCEPTRE to follow a hundred or more cycles of the 30 MHz ringing in order to obtain the envelope of the transient response.

The results of the computer simulation are compared to the wave shapes measured in the receiver when the antenna/receiver system was exposed to the fields of the IIT Research Institute Crystal Lake Simulator and the Harry Diamond Laboratories Woodbridge EMP Simulator.

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*This work is supported by Harry Diamond Laboratories (Lab. 1000), Woodbridge, Virginia, under Contract DAAG39-72-C-0192.

SYSTEM LEVEL CONSIDERATIONS SECTION

Session C-1A

Thursday Afternoon 27 September 1973

Chairman: A. A. Cooper
Sandia Laboratories

# EMP Response of UHF Phased Array Antenna to Field Strengths $\leq$ 1 kV/M

BY U. Cocca, R.C. Fries, and L.C. Humphrey
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The following outline is for your review and consideration for presentation at the Joint EMP Technical Meeting 25-27 September 1973. This outline should not be released for public use until approval is received from General Electric Company.

OUTLINE:

I. Simulation of EMP at laboratory test facility

1. Input source characteristics
2. Spectral content of source
3. Extraneous signals induced in measurement cables
4. Antenna orientation effects
5. Spectrum analysis of EMP field

II. Results of UHF phased array antenna exposed to simulated EMP.

1. Time and frequency domain analysis and test programs
2. Response data on radar control electronics
3. EMP assessment of UHF phased array antennas

# EMP Response of UHF Phased Array Antenna to Field Strength $\leq$ 25 kV/M

BY U. Cocca, R.C. Fries, and L.C. Humphrey
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The following outline is for your review and consideration for presentation at the Joint EMP Technical Meeting 25-27 September 1973. This outline should not be released for public use until approval is received from General Electric Company.

OUTLINE:

I. High Voltage EMP simulation results

1. Input source pulse generator - time and frequency domain data
2. Fields within parallel plate transmission line simulation as a function of location
3. Time and frequency domain response of UHF phased array antenna dipoles and radar control electronics

II. Analysis and test program

1. Spectral analysis of low repetition rate EMP
2. Field evaluation using E and B field sensor
3. Error analysis
4. Investigation of non-linear effects
5. Measurement of maximum coupled voltage and energy into radar system

III. Comparison of analytic assessment techniques with measured data for evaluating EMP coupled into UHF phased array radar antenna.

JOINT ELECTROMAGNETIC PULSE TECHNICAL MEETING

Classification of Presentation: SECRET RESTRICTED DATA

Authors: Dennis E. Grimes, Radiation Effects Technology
Thomas P. Henry, AWACS Systems Engineering

Organization: Engineering Department
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Proposed Paper Title: The AWACS Surveillance Radar Antenna In A High Altitude Threat Level EMP Environment (U)

## ABSTRACT

(U) The AWACS Surveillance Radar employs a large planar array antenna which may be exposed to high altitude threat level EMP. The antenna and peripheral equipment is described and a worst case analysis of its reponse to the specified double exponential approximation of the external field is presented. Several different angles of incidence and steering angles are considered and the associated system response analyzed. The protection techniques which are incorporated in the AWACS Radar system are discussed.

ABSTRACT

SYSTEM LEVEL EMP
VULNERABILITY AND HARDENING ASSESSMENT


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McDonnell Douglas Astronautics Company initiated a program to evaluate the EMP vulnerability of the Spartan missile in 1969 as a part of the overall Spartan nuclear vulnerability and hardening program. This EMP vulnerability assessment program addressed all phases of operation from ground installation through target intercept. Vulnerability evaluation included analytical predictions of the ground and missile equipment response to EMP, equipment susceptibility analysis, component susceptibility testing, subsystem analysis and response testing, and finally system level testing at the ARES facility. This program is near completion and much of the results are documented in a series of technical reports. This paper summarizes the overall program results. An appraisal of the techniques used on this program is made to help guide future system vulnerability and hardening programs.

This paper is recommended for inclusion in technical area f (System Level Considerations) and will be classified Secret Restricted Data.

C-1A-5

# ANALYTICAL AND EXPERIMENTAL TECHNIQUES EMPLOYED IN THE EMP EVALUATION OF THE LANCE MISSILE SYSTEM

R. A. Pfeffer and H. G. Mueller

Harry Diamond Laboratories

ABSTRACT CLASSIFIED

ABSTRACT

# SYSTEM LEVEL IEMP VULNERABILITY ASSESSMENT

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The results of a major NV&H program to assess the hardness of a specific missile system to IEMP effects will be discussed. In order to evaluate the system response and susceptibility to this complex radiation environment, a multi-phase program was carried out. The response phase addressed the bulk cable current expected in the system wiring by a series of coupled analytic and test studies. The susceptibility phase addressed the problem of blackbox upset and burnout to the predicted pulse waveform. The response was then compared to the susceptibility test results to yield a vulnerability statement. The response program included analytic work (theoretical and numerical) on the electron emission induced by the radiation, the space charge limiting of the electrons, and the breakdown of the space charge barrier as a function of radiation pulse width and air density excitation of the interior cavity fields and the coupling to cables. Four classes of response verification testing were employed to appraise the validity of the analysis. These include (1) missile cavity current injection testing (CIT), (2) flash x-ray testing (FXR), (3) underground testing (UGT), and (4) electron beam simulation (e-beam). The details of these various testing procedures, their advantages and disadvantages, and correlation to pre and posttest predictions will be discussed in this paper.

A comparison of the susceptibility analysis with the blackbox susceptibility data developed using high level current injection techniques is shown. Additional hardening technique studies, suggested by the analytic and response verification test results, were pursued and are discussed.

This paper is recommended for presentation as a part of technical area f (System Level Considerations), and will be classified Secret Restricted Data.