THE LAWRENCE LIVERMORE LABORATORY DATA BASE FOR
EMP EXTERNAL COUPLING: SYSTEM RELIABILITY*Robert M. Bevensee and Hriar S. Cabayan
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This paper describes the external coupling data base prepared by Lawrence Livermore Laboratory for EMP assessment. The data may be used either by electromagnetic specialists or by engineers who may have only limited knowledge of the subject. Data generation by computer code and Transient Electromagnetics Range is described. The modular (generic system) form of the base is outlined, with examples, from a worst-case viewpoint. Validation data for the Range are given. Illustrative simulation test data on a real system are compared to canonical and representative model data. The close agreement validates the links between the real system/canonical model and real system/representative model. Validation from other test data establishes the wide scope of the base for EMP prediction/estimation.

1. Introduction

The Electromagnetic Pulse (EMP) Interaction and Coupling Modules¹ have been prepared by the Lawrence Livermore Laboratory to make fundamental data on the EMP responses of structures available to protection engineers. The modules may be used either by electromagnetic specialists or by engineers who may not have a great deal of knowledge of the subject. Module in this context denotes a self-contained package of information about the EMP response of a generic class of structures. In each module, a canonical model represents a generic class of systems such as missiles, ships, airplanes, etc. The intent is to provide pertinent external coupling information to permit reasonable cost-effective estimates of the quantities (currents, voltages, energies, etc.) involved in estimating the hardness of a system to the effects of EMP.

This set of modules addresses the so-called external coupling problem: assessing how much EMP energy couples into a system via an external antenna, inadvertent or otherwise. Data are given to estimate the EMP response of an equivalent load at the input terminals of various antenna configurations. The load represents the internal system connected to the antenna.

The modules share a common set of assumptions, that is, philosophy of approach, EMP threats, scaling techniques, and organization.

The diagram presented in Fig. 1 shows three nodes representing information sources and validation and approximation links between them. The information sources are further described in Table 1. A canonical model may be thought of as representing -

electromagnetically - a generic class of systems such as missiles, ships, airplanes, etc. Missiles, for example, by virtue of their very shape (generally long and thin) fall into a specific category or class from an electromagnetic standpoint. Thus, one can assign them all to one class represented by a straight-cylinder canonical model. To determine how "good" our canonical models are, we consider the paths from the real world to the model world as illustrated in Fig. 1. The direct path (upper validation link) involves using test data taken on a real system which the canonical form is supposed to represent. If fairly good agreement is achieved, we can ascertain that the particular canonical model is indeed descriptive of the real system.

The other route is somewhat indirect but equally important as a validation link (lower path). By constructing a representative model of a real system (ship, missile, etc.), for example a scale model of a "typical" missile, and by determining how good an approximation to this model a canonical form is, we can again make significant approximations of the currents, voltages, etc., that

Fig. 1. Information Sources for External Coupling Modules.

would appear at corresponding points in the real system. Throughout these modules such "representative" models are detailed scale models, either measured or analyzed with computer codes. This is the rationale for the format of the coupling information provided in this document.

The data in the modules are presented in two levels. Level A consists of scalar worst-case data, such as total energy absorbed by a load, peak load current or voltage, and peak power absorbed. These data are primarily in the time domain and are provided over a wide range of parameter variations. Level B data consist of more detailed frequency and time information, such as input impedance and effective height in the frequency domain, load power and cumulative energy absorbed in the frequency domain and load current or voltage and power absorbed in the time domain. Because these data are more detailed, fewer parameter variations are covered.

The organization of this paper is as follows. In Section 2, we give a succinct

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Table 1. Description of Information Sources in Fig. 1

Terminology	Example	Data Generation	Type of Data
Canonical Model	Canonical Model represents whip-on-box Generic Class whip-on-ship whip-on-tank	Computer prediction or electromagnetic Range tests	Levels A and B parameterized
Representative Model	Scale model of ship, tank, jeep computer stick model of plane	Computer predictions or electromagnetic Range test	Levels A and B model specific
Real System	Ship, tank, missile, log periodic antenna	Full-scale simulator tests	Levels A and B system specific

description of the external coupling problem and place it within the overall EMP assessment and hardening problem. In Section 3, we describe the derivation of the antenna equivalent circuit at the load terminals, either by computer code or Transient Range measurements, and the data processing to obtain the EMP response of life-size structures, and in Section 4, we present sample EMP response data vs. geometry and load resistance from a "worst-case" viewpoint. In Section 5.1, we validate the Range measurement procedure by comparing f- and t-domain responses of simple structures with their computed responses, and in 5.2, we provide comparisons that relate EMP simulation test data on one system (Army GRC-106 Monopole System) to modular data, and thus illustrate applicability of the LLL data base for system designers.

2. Problem Description

The data modules¹ described in this paper are intended to answer directly the question of how much EMP excitation couples through the envelope of canonical, generic, and scale-model specific systems of interest via antennas only. The modules do not furnish direct answers to the questions of how the excitation distributes itself with the system (external-internal coupling problem) and how much excitation couples into sub-systems and components (internal coupling problem).

The modules are written for the EMP protection engineer who is faced with the problem of extrapolating data from relatively simple canonical and generic configurations to the specific, usually complicated, systems of interest to him.

The overall EMP problem really concerns all matters pertaining to protection or hardening decisions and their full implementation from conception of design to actual deployment of the system. The overall problem, if one concentrates on hardening as the central issue, would involve research and development in the following major phases of hardening protection engineering activity: conceptual, validation, development, production, and deployment.

In the conceptual phase, whether the system already exists or not, it is necessary to make assessments of threat environment and system sensitivity to determine if hardening is necessary. Hardening requirements are postulated, and validated and refined estimates of vulnerability are provided. Carrying a system through all of the above phases represents an extensive overall

systems EMP problem, at least for complex major systems. Clearly, problems of external coupling can occur in any of the phases, because normally different groups and different requirements are present. For example, in developing configuration planning in the conceptual phase, rapid changes could be taking place that require new estimates of coupling. In deployment, perhaps several years later, some estimates for test or maintenance purposes may be necessary. Engineering changes to the system during production or preproduction may require rapid estimates of coupling. Thus, a source of readily available information regarding coupling effects can influence decisions in all phases.

To see how simplified structures such as loops, straight wires, wires or loops on boxes, wires or loops on cylinders, etc., are involved in the external coupling problem, it is only necessary to think about or inspect several different types of systems and their physical embodiments. For example, a launched missile or projectile proceeding in air towards a target could be approximated by a cylindrical wire in free space for EMP coupling purposes. Similarly, such a missile could have an appendage such as an external cable or conduit which forms either a loop or wire on a cylinder approximation for external coupling analysis. A vehicle or a building in a facility would resemble a box or cylinder with external appendages such as whip antennas, microwave towers, or lights. A bomb or an artillery shell would resemble a longer guided missile in basic structure.

Clearly then, much time and effort could be saved and a greater awareness of the problem would be obtained if a reasonable small set of simplified canonical structures would suitably approximate the very large number of system specific elements for external coupling analysis. This report provides comparisons that relate EMP simulation test data on system physical elements (such as missiles, aircraft, radios, and vehicles) to data compiled from computer calculations and Transient Range experiments for the simplified structures. The analytical data provide much more information than normally available from an EMP simulation test. Such data include peak load currents, total energy, peak load power, peak load voltage, and pulse width. The large range of parameters and the great amount of data taken for several types of geometrically different but basic structures such as loops, wires, cylinders, in several configurations, will permit a rapid analysis and scaling for many external coupling situations found in

real systems.

3. Method of Data Generation

The fundamental problem is that of generating the frequency-domain equivalent circuit parameters of the antenna configuration at the load terminals. From this circuit, the spectral and temporal response of any load to any temporal variation of the incident wave may be readily computed. The plane wave assumed was the 2-term exponential commonly used in EMP assessment (nominal EMP)².

Equivalent circuit information was obtained directly in the time domain, either from a computer code for relatively simple wire structures or by scale model measurements on the LLL Transient Electromagnetic Measurement Facility (Range) of more complicated structures. It was vastly more efficient to obtain f-domain information in the important EMP range of $L/\lambda \lesssim 1$ (L = antenna length) by Fourier transformation of t-domain data.

The f-domain antenna equivalent circuit parameters of effective height $h_e^S(f)$ and input impedance $Z_a^S(f)$ of a full size structure S times larger than the scale model analyzed are obtained as

$$h_e^S(f) = S h_e(Sf) \quad (1a)$$

$$Z_a^S(f) = Z_a(Sf) \quad (1b)$$

Once these circuit parameters at the reference terminals for the load are obtained, the EMP response of a given load is predicted by exciting the circuit by the spectrum of the incident EMP field to obtain the frequency-domain load current, energy dissipated, etc., and then inverse Fourier transforming the current and/or voltage response to obtain peak temporal current, instantaneous power dissipated, etc., in the specified load.

3.1 Numerical Computation By Computer Code

The time-domain code WT-MBA/LLLLB³ is used to compute the currents on, and the radiated or scattered fields from, an arbitrary antenna or scatterer with resistive or complex load which has been excited with a specified time-varying electric field. The code solves an electric field integral equation, reduced by the subsectional collocation version of the method of moments to a form which can be handled on the CDC 7600 computer at LLL.

To evaluate the equivalent circuit input impedance at a wire segment, a Gaussian voltage generator was connected in series and the input current computed to some specified time, beyond which it was extrapolated. The discrete Fourier transform then yields the f-domain input impedance. For the scattering case, with a convenient load attached, the antenna was excited by an incident plane wave of Gaussian time variation, and the load current response $I_L(t)$ obtained and Fourier transformed to the frequency domain. With the incident field E^{inc} and input impedance Z_a also known the effective height $h_e(f)$ is readily obtained. The equivalent circuit for the wire configuration at the load terminals

is therefore completely determined for the EMP response of any linear load.

3.2 Transient Range Measurements

A schematic diagram of the Transient Range⁴ at the Lawrence Livermore Laboratory is shown in Fig. 2. In essence, a pulser*

Fig. 2. Schematic of the Range, showing operation in either the TDR or scattering mode.

with a Gaussian-like pulse is used in either of two modes of operation: (a) the time-domain reflectometry (TDR) mode, in which the test target is excited through one arm of a precision power divider and the reflected temporal signal from another arm is data processed to obtain the input impedance $Z_a(f)$ from the reflection coefficient and (b) the scattering mode, whereby the conical transmitter is pulsed and the scattered signal is picked up from the test target and data processed to obtain the effective height $h_e(f)$. With $E^{inc}(f)$ of the conical transmitter calibrated and load voltage $V_L(t)$ measured, $Z_a(f)$ already known, and $Z_L(f) = Z_o$ of the coaxial cable the F-transforms of E^{inc} and V_L yield for h_e

$$h_e(f) = \frac{Z_a(f) + Z_L(f)}{Z_L(f) E^{inc}(f)} V_L(f) \quad (2)$$

The "clear time" is about 20 nsec before unwanted reflections occur from the surroundings. Generally the antenna response was so small at 20 ns that it was "zero-filled" to 40 ns to reduce the frequency discrimination Δf .

Of the measurement errors, the systematic ones caused by imperfect cables, frequency-dependent components, etc., were negligible compared to certain statistical ones. The pulser amplitude and time-base jitter during the repetitive measurements when the sampling

*An IKOR EMP model: pulse width, ≈ 300 psec; amplitude, ≈ 1.2 kV; rep. rate, ≈ 200 pps. An NBS built pulser, with the corresponding parameters of ≈ 150 psec; ≈ 14 V; 5×10^4 pps was also employed for some measurements.

scope averaged M measurements of each of N consecutive points in a temporal waveform ($M = 4$ or 16 ; $N = 1024$) were negligible. It was extremely important to operate the scope with full-scale deflection to utilize full dynamic range. System noise predominantly due to scope noise triggered by the pulser and large near 0.25 GHz was minimized by maintaining the scale model antennas longer than 10 cm.

The effects of all statistical variations were assessed by processing the Range TDR and scattering measurements independently on various days for a 30 cm antenna on a whip-on-box and loop-on-box configuration. The statistical uncertainties are summarized in Table 2.

Table 2. Statistical Errors in Temporal EMP Responses Derived from Range Measurements For Whip and Loop Antenna Configurations. L is antenna length. $(P_L)_{av} = W_L/T_W$, T_W being the 10-90% pulse width.

Response	Errors (in db)
W_L , load energy	≤ 2 , less at higher L
$(I_L)_P$, peak load current	≤ 4 , less at higher L
$(V_L)_P$, peak load voltage	≤ 4 , somewhat less at higher L
$(P_L)_P$, peak load power	≤ 2 , for whip-on-box configuration ≤ 5 , for loop-on-box configuration less error at higher L
$(P_L)_{av}$, average load power	≤ 5 , somewhat erratic over the range $1 \leq L \leq 100$ m

4. Description of the Data Modules

4.1 Example of Range-Generated Data

Fig. 3 shows a test target whip antenna-on-box configuration measured to obtain the equivalent circuit parameters and hence the EMP responses of real-life structures scaled up by various values of S , (Eq. 1). This fixed-size box with variable length whip is intended to represent generically a real-life structure such as a whip on a well-shielded building sitting on a high-conductivity ground. To a lesser extent physically (but to a rather close approximation electrically) it represents a whip-on-tank.

The vertically polarized $\vec{E}_{inc}$ simulates a "worst-case" incident wave, and a representative value of $\Omega = 2 \ln(2L_W/a) \approx 12$ was selected. Measurements were taken with a whip in one of the three positions and of length $L_W = 15, 30$, or 60 cm; the reference dimension D was taken to be 51.2 cm. Thus, measurements were taken and processed to yield the equivalent circuit parameters for $D/L_W = 3.4; 1.7$, and 0.85 . The circuit was then scaled to put L_W in the range $1 \leq L_W \leq 100$ m and the EMP responses were computed for the plane-wave normally incident EMP field. The ground plane effectively doubled this incident field.

The resultant peak voltage contours in the D/L_W - L_W plane are shown in Fig. 4 for the edge whip and $R_L = 300$ ohm (essentially the self-consistent "worst-case" value). From Fig. 4, we choose the value $D/L_W = 0.85$

Fig. 3. Whip-on-box configuration on the Range.

as approximating "worst-case" for any L_W and recompute the $(V_L)_P$ -response contours in the R_L - L_W plane. These are shown in Fig. 5. We see that the value $R_L = 300$ is indeed approximately "worst-case" with respect to both D/L_W and R_L for all L_W .

Similar comparisons of load energy, etc., data in the D/L_W - L_W and R_L - L_W planes for various configurations shows that $R_L = 300$ is a nearly self-consistent worst-case load with respect to all parameters, within experimental uncertainties.

4.2 Summary of the Modular Data

The EMP data reported illustrates the emphasis in the modular data on "worst-case"

Fig. 4. $(V_L)_P$ contours in the D/L_W - L_W plane for edge whips; $Z_L = 300$ ohm.

Fig. 5. $(V_L)_P$ contours in the R_L - L_W plane ($X_L = 0$) for the edge whip-on-box; $D/L_W = 0.85$.

parameters and "worst-case" EMP responses of various generic configurations with respect to incident wave, geometry ($D/L, \Omega$) and load (position, when possible, and usually resistive). The modules are entitled

- I. Introduction
- II. Straight Wire
- III. Loop
- IV. Whip on Box (Fig. 3)
- V. Whip on Cylinder (horizontal half cylinder, full vertical cylinder)
- VI. Loop on Box
- VII. Loop on Cylinder
- VIII. Whip-in-Wedge
- IX. Wing Roots
- X. System Relatability and Applications

A table was prepared to indicate which antenna configurations and D/L values gave "worst-case" EMP response (relative to both D/L and R_L) in modules IV-VIII for each response. In some cases, two different configurations in a module gave worst-case response, or nearly so, depending on the range of L .

5. Validation of Transient Range Data and EMP Predictions from the Data Modules

First we discuss the validation of the input impedance and scattered field measurements on the Transient Range by computer code computations in the same geometry. Then we compare field test data taken on a more practical structure with computations of similar response data as derived from the appropriate data modules. The agreement between measured and estimated responses validates the usefulness of the data modules for estimating EMP responses of practical, real-life configurations.

5.1 Validation of the Transient Range Operation

We compared the measured input impedances of a monopole and half-loop on the ground plane with computations from code WT-MBA/LLL1B. (The accuracy of Z_a affects the accuracy with which effective height is measured.) Good agreement was obtained for both structures beyond $L/\lambda = 3$.

To validate the scattered voltage ($V_L(t)$) measurements, the computer code was used on a model of the experimental set-up consisting of straight-wire transmitter with the actual pulsed excitation and test target in its correct position on the ground plane. (The difference in test target response between this transmitter and the narrow-angle conical transmitter was negligible.) For this validation, the effective height $h_e(f)$ as an intermediate variable was not needed. Both temporal and spectral short-circuit current I_s , as computed agreed well with the measured responses, for the monopole and for the half-loop.

The good agreement of measured and computed spectral data well beyond $L/\lambda = 1$ for both these structures validates the Range measurements of input impedance and scattered voltage of whips and loops on various structures in the important frequency interval for EMP effects.

There is a data processing error in $h_e(f)$ caused by the fact it is derived for a test target relatively close to the transmitter in Fig. 2, where the incident field is not plane-wave, whereas it is used in the equivalent circuit (usually scaled) to deduce the load response to plane-wave EMP.

The effect of the shape of E^{inc} was studied by computing the response of the 30-cm monopole and half-loop on the ground plane for point-excitation (from the transmitter at the ground plane) and also plane-wave excitation. The results indicate the differences are not serious out to $L/\lambda \approx 1$.

In fact, the differences in all the temporal EMP response contours (load energy, peak current, etc.) of the scaled-up monopole are entirely negligible, and are somewhat greater, but still negligible, for the scaled-up 30-cm loop on ground plane. This insensitivity of EMP response to the shape of E^{inc} is rather surprising considering the sizes of the monopole and half loop on the Range relative to the distance of load from transmitter apex, about 1.3 m.

5.2 System Validation

In Module X, the transient responses of seven military systems measured in the field are compared to predictions from the model world, i.e., canonical models and/or representative models. The straight wire canonical model is the simplest, followed by the whip-on-box of appropriate shape. In addition, predictions from a more complex representative model are presented whenever available.

Below, we present illustrative results for the Army GRC-106 Monopole System⁵, tested by IITRI at the Crystal Lake Low-Level EMP Simulator (vertical polarization). The 17.2 ft. whip antenna is mounted on a 6-by-6-by-6 ft. communication van that houses the GRC-106 receiver. The whip connects to an insulated, nonshielded cable that passes through a plate in the side of the enclosure and then to the receiver about 6 ft. away. The return path for the current is the shielded enclosure itself.

5.2.1 Real System Test Results. The real part of the antenna input impedance, $R_i(f)$, measured where the whip joins the cable, is shown in Fig. 6 (solid line). The imaginary part, $X_i(f)$, is depicted in Fig. 7 (solid line).

When the configuration was exposed to the field $e_i(t)$ at the IITRI Crystal Lake EMP Simulation Facility, shown in Fig. 8, the peak voltage and current measured at the receiver were: $v_R(t)_p \approx 10V$ and $i_R(t)_p \approx 320$ mA.

5.2.2 Model World Predictions; Canonical Straight Wire. We grossly model the whip by a monopole of length $L = 5.24$ m on a highly conducting ground plane and load $R_L = 100$ ohm, thus neglecting the presence of the shielded

Fig. 6. Real Part of Antenna Input Impedance for Whip on Enclosure.

Fig. 7. Imaginary Part of Antenna Input Impedance for Whip on Enclosure.

enclosure. The response of this whip to the net incident electric field is computed in three steps: (a) compute the response of an equivalent straight wire in free space to nominal EMP; (b) correct for the actual incident electric field by using a simple scaling rule; (c) obtain the monopole response from the preceding response of the straight wire.

In step (a), we obtain the response $(V_L)_p$ for a wire of length $L'_w = 10.48$ m and load $R'_L = 200$ ohm from Fig. 9 as: $(V_L)_p = 1.0 \times 10^5$ V.

Fig. 8. IITRI Crystal Lake Low-Level EMP Simulator Electric Field.

In step (b), we observe that a good estimate for the peak current response for any E^{inc} may be obtained from that for nominal EMP, E^{EMP} , by multiplying $(I_L)_p$ for the latter by the ratio,

$$\int_0^T E^{inc}(t) dt / \int_0^{T'} E^{EMP}(t) dt, \quad (3)$$

where

$$T = \min \begin{cases} \text{time } E^{inc} \text{ first crosses zero} \\ \text{time first reflection arrives at load point} \end{cases}$$

and T' is the time the first reflection occurs at the load point. We approximate

$\int_0^T E^{inc}(t) dt$ by one triangle up to the time $L'_w/2c = 17$ nsec of the first reflection from the end of the straight wire, since this time is less than the zero-crossing time of ≈ 125 nsec on Fig. 8. The integral is $\approx 20 (17/2) = 170$ V/m nsec. The corresponding integral for nominal EMP is $\approx 5 \times 10^4 \times (10/2 + 7) = 6.0 \times 10^5$ V/m nsec. Since E^{inc} of Fig. 8 corresponds to twice nominal EMP, including ground reflection, our correction factor for $(V_L)_p$ of (a) is 1.4×10^4 .

In step (c), we obtain the monopole response $(V_L)_p$ to E^{inc} of Fig. 8 from the free-space straight-wire response in (a) and the correction factor in (b) as $(V_L)_p = 14$ V.

This is the straight-wire model estimate of peak load voltage across $R_L = 100$ ohm at the whip base. Choosing $(V_L)_p$ as the worst value, we assume this peak voltage on the $Z_0 = 100$ ohm transmission line is incident on the receiver of input impedance $Z_R = 50$ ohm. The total peak voltage at the receiver will

Fig. 9. R_L versus L , with peak load voltage $(V_L)_p$ as parameter. Fatness factor $\Omega = 10$. Nominal EMP.

therefore be $2 Z_R / (Z_R + Z_0) = 100/150 =$ two-thirds times that incident, i.e.,

$$(V_R) \approx 14 \times 2/3 \approx 9 \text{ V.}$$

The estimate of $(I_R)_p$ is just $(V_R)_p / 50 = 180$ mA.

5.2.3 Model World Predictions; Canonical Whip-on-Box. The edge whip-on-box model of Fig. 3 was selected as being the closest approximation to the representative configuration. First, the level A peak voltage and current were computed for a whip-on-box

scaled up to have a whip of the same length $L_w = 17.2' = 5.24$ m and the same D/L_w ratio, 0.35, and nominal EMP excitation. These responses were corrected for the simulation incident electric field in Fig. 8. Then the level B input impedance $Z_I(f)$ was computed for an edge whip-on-box with $L_w = 60$ cm = 1.97 ft. $Z_I(f)$ was then scaled to apply to the scaled-up whip-on-box model with $L_w = 17.2$ ft.

(A) Level A Data. For the edge whip-on-box of Fig. 3 with the same $D/L_w = 0.35$ and $L_w = 5.24$ m as the representative system and with load $R_L = 100$ ohm, we estimate $(V_L)_p$ from Figs. 4 and 5 by interpolation. A characteristic impedance of $Z_0 = 100$ ohm is estimated by IITRI for the transmission line formed by the bare cable and shielded enclosure.

For $D/L_w = 0.35$, $R_L = 300$, we estimate on Fig. 4 $(V_L)_p \approx 3 \times 10^5$. On Fig. 5, the reduction factor for changing R_L from 300 to 100 ohm is $(V_L)_p(100 \text{ ohm}) / (V_L)_p(300 \text{ ohm}) \approx 1/3$. Hence our first estimate of $(V_L)_p$ across $R_L = 100$ is

$$(V_L)_{p1} \approx 3 \times 10^5 \times 1/3 = 1.0 \times 10^5 \text{ V.}$$

For our second estimate, we notice for $D/L_w = 0.85$ and $R_L = 100$ ohm on Fig. 5 $(V_L)_p \approx 1.2 \times 10^5$. On Fig. 4, the reduction factor for changing D/L_w from 0.85 to 0.35 is 2.5/3. Hence our second estimate is

$$(V_L)_{p2} \approx 1.2 \times 10^5 \times 2.5/3 = 1.0 \times 10^5 \text{ V,}$$

which is coincidentally equal to $(V_L)_{p1}$.

By previous remarks in the approximation by canonical straight wire, the peak voltage at the receiver is about two-thirds of this,

$$(V_L)_p \approx 1.0 \times 10^5 \times 2/3 = 0.67 \times 10^5 \text{ V.}$$

This estimate must be corrected for the ratio of amplitudes of the simulation incident field of 20 V/m (and 15 ns rise time, Fig. 8) and the nominal EMP field of 100 kV (including ground reflection and 10 ns rise time). Thus, our final approximation of receiver peak voltage is

$$(V_R)_p \text{ approx } \approx 0.67 \times 10^5 \times \frac{20}{10^5} = 13.4 \text{ V.}$$

The approximation to receiver peak current is $1/Z_R$ of this or $(I_R)_p \approx 13.4/50 = 268$ mA.

(B) Level B Data. As stated earlier, the input impedance $Z_I(f)$ of the canonical edge whip-on-box of Fig. 3 was measured on the LLL Transient Electromagnetic Range. Whip length was $L_w = 60$ cm = 1.97 ft. The impedance $Z_I^S(f)$ for the scaled-up model, scaled by factor $S = 17.2/1.97 = 8.73$ was obtained from the relation

$$Z_I^S(f) = Z_I(8.73f),$$

plotted as dashed lines in Fig. 6 and Fig. 7.

5.2.4 Comparison Between Measurement and Prediction The whip-on-box model estimated peak receiver voltage is 13.4 V; the straight-wire model estimate was 9 V, which is coinci-

dentally also closer to the measured value of 10 V. Both estimates are realistic first estimates of the simulation-threat voltage actually measured by IITRI.

The discrepancies are partly explained by the fact the receiver input impedance is apparently closer to 31 ohm rather than the 50 ohm assumed in the modeling.

The level B input impedance data from the whip-on-box model agree very well with the impedance measured on the representative system. The agreement is remarkable considering that the IITRI whip is mounted just beyond the edge of the top surface, while the LLL whip in Fig. 3 is mounted just inside the edge.

6. Conclusions

The modules show that the EMP data adequately approximate the EMP responses of scaled-up, life-size representative models, such as whip-on-tank, as deduced from Transient Range measurements. In addition, the responses of these models are compared with field measurements taken on the real-life counterparts. The good agreement between scale model predictions and real-life measurement serves to validate the scale-model Range measurements and EMP data-processing techniques.

More important, the validation shows that EMP responses derived for simpler canonical systems will, when extrapolated, often adequately estimate the EMP response of the real-life system. Thus, the EMP responses derived for simple modular systems prove useful for estimating the EMP responses of enormously more complicated real-life systems for the external coupling problem.

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References

1. R. M. Bevensee, et al, "External Coupling of EMP to Generic System Structures," Lawrence Livermore Laboratory, M 090, April 1978.
2. "EMP Engineering and Design Principles," Bell Laboratories, pg. 28, 1975.
3. J. A. Landt, E. K. Miller, and M. Van Blaricum, "WT-MBA/LLLB: A Computer Program for the Time-Domain Electromagnetic Response of Thin-Wire Structures," Lawrence Livermore Laboratory, UCRL-51585, May 1974.
4. R. M. Bevensee, F. J. Deadrick, E. K. Miller, and J. T. Okada, "Validation and Calibration of the LLL Transient Electromagnetic Measurement Facility," Lawrence Livermore Laboratory, UCRL-52225, March 1977.
5. "Effects of EMP on Military Systems," IITRI E6238, February 1974.
6. J. A. Landt, "Peak Current Estimates: Cylinders in Free Space with Extensions to Other Structures," Nuclear EMP Protection Engineering and Management Note, PEM-32, July 1974.

Spectral Response of Cables

We wish to consider the normalized response of cables vs incident spectrum. In order to do so we must compare the response of identical samples. In addition to the results obtained in this work we also report results from the following spectra:

1. SPI Pulse-6000: 2-1/2" cathode, 200 kV diode charging voltage, obtained from Reference 8.
2. Aerospace Dense Plasma Focus: 8 spectra, obtained from References 10 and 11.

The comparisons are made in Table 2. We have ordered the spectra by the number of rads (Si) that each spectrum yields per cal/cm². In other words, reading Table 2 from left to right, the spectra goes from soft to hard.

We make the following observations concerning Table 2

1. The results from the various spectra compare favorably, with usually much less than an order of magnitude difference between the lowest and highest spectral response of a given cable.
2. For the semi-rigid cables there does not appear to be a pattern in going from soft to hard spectra. However, for braided cables there appears to be a peak occurring at the SPI-2-1/2 spectrum, which corresponds roughly to a 12 keV Black-body spectrum.

Conclusions

We have pulled together a quantitative comparison of SGEMP hardening approaches for cables in Table 3. However, there are other considerations in selecting cables for satellites than merely SGEMP response which is just one of the ingredients of the tradeoff matrix, and some of the hardening approaches present serious disadvantages in terms of weight penalties and lack of flexibility (e.g., semi-rigid cables), and difficulty in making and maintaining connections (e.g., aluminum cables).

One possibility that seems most promising and has yet to be optimized is the use of conductive plastic coatings on the conductors. Of the samples we have tested only the shield-insulation interface has been treated. One could imagine treating the center wire(s) as well. In addition, reducing the resistivity of the conductive plastic by an order of magnitude seems possible, based on our discussions with Raychem. The

main operational advantage is that it maintains the braided cable's flexibility.

We believe that the MCCABE model of x-ray response of cables is verified to about a factor of two for braided cables. For semi-rigid cables the model works less well, and we feel that this has more to do with uncertainties in assigning the gaps than in the model itself. In any case the relative response of cables which the MCCABE code predicted as a function of the various parameters, such as shield thickness, gap size, materials, etc. has been verified by the experimental results.

References

1. V. van Lint, "Radiation-Induced Currents in Coaxial Cables," IEEE Trans. Nucl. Sci. NS-17, 210 (1970)
2. R. L. Fitzwilson, M. J., M. J. Bernstein and T. E. Alston, IEEE Trans. Nucl. Sci. NS-21, 276 (1974)
3. D. M. Clement, C. E. Wuller and E. Paul Chivington, "Multi-conductor Cable Response in X-ray Environments," IEEE Trans. Nucl. Sci. NS-23, 1946 (1976)
4. W. L. Chadsey, B. L. Beers, V. W. Pine, C. W. Wilson, "Radiation-Induced Signals in Cables," IEEE Trans, Nucl. Sci. NS-23, 1933 (1976)
5. D. M. Clement and C. E. Wuller, "Assessment of Cable Response Sensitivity to Cable and Source Parameter in Low Fluence X-ray Environments," DNA 4407 T, 8 April 1977
6. D. M. Clement and R. A. Lowell, "The Hardening of Satellite Cables," DNA-4540, 28 February, 1978
7. R. A. Lowell, "X-Ray Characterization of the SPI-PULSE 6000," SPIRE TR-77-12, March, 1977
8. D. M. Clement, L. C. Neilsen, T. J. Sheppard and C. E. Wuller, "Stored Charge Release in Cables in Low-Fluence X-Ray Environments," IEEE Trans. Nucl. Sci. NS-24, 2422 (1977)
9. D. M. Clement and C. E. Wuller, "MCCABE: A Code for Calculating X-ray Induced Currents in Shielded Cables," DNA-4541F, 28 February, 1978
10. F. Hai, P. A. Beemer, C. E. Wuller and D. M. Clement, "Measured and Predicted Radiation-induced Currents in Semi-rigid Coaxial Cables," IEEE Trans. Nucl. Sci. NS-24, 2435
11. F. Hai, "Summary of Cable Response Experiments," 15 July 1977, SAMSO-TR-77-151.