ELECTROMAGNETIC RESPONSE PREDICTION TECHNIQUES

INTRODUCTION

The survivability of electrical/electronic systems to severe electromagnetic environments, lightning, EMP, EMI, ECM, etc., is often a design requirement for which a system level design approach is not commonly available. This article details the techniques that can be utilized to predict electromagnetic (EM) and functional responses induced in electrical/electronic equipment by an external EM environment although EMP acting on a communication facility is used for discussion purposes, responses to other EM environments such as lightning and EMI can be similarly obtained.

The EMP response of a facility can be predicted using electrical and functional models to represent the facility configuration. The electrical model represents the electromagnetic coupling from an external EMP environment to sensitive electronic components within the facility. Using the electrical model and the external EM environment, wave-forms are calculated at the inputs of critical components. These wave-forms are then compared with component upset and/or damage thresholds to develop probabilities of component disruptions. The functional model relates these probabilities and the various functional response parameters which describe the functional operation of the facility. The development of this predictive capability used an iterative process of prediction and test where predictions were developed prior to any testing. The data provided by testing then were used for evaluation and refinement of the predictions and techniques. These refined techniques can be utilized for future pretest predictions and evaluation tests. Proceeding this way leads to a validated prediction technique for use on untested facilities and thus reduce the requirements for testing.

The computer code capability that implements these techniques is a very important factor in the practical application to facility response predictions. The computer code, PRESTO, is capable of handling very large mathematical models, the limit being a function of the number of nodes and circuit elements in the model as well as the structure of the models and submodels, the number of source terms, and the number of desired output responses. Models entailing in excess of 2000 nodes and some 280 transmission line and rack submodels are solved routinely.

FACILITY DESCRIPTION

The physical data necessary for EMP response predictions depend upon electromagnetic coupling features and upon the facility functions and equipment. The electromagnetic and functional descriptions are defined from engineering drawings and visual inspection of the facilities.

The electromagnetic description of the facility must include the length and orientation of the external and internal cables and conductors. The facility structure must also be evaluated as this is an important factor in determining the degree of shielding for external fields. The equivalent circuits of the coupling paths from penetrations to internal cables and equipments require detailed description to properly define the equipment circuits.

The functional description for a communication facility consists of equipment lists, the functional description by equipment group, and the functional events and timing between the various equipments. The operational manuals provide an important baseline of data which are supplemented by descriptions of individual site unique equipments and operational procedures.

ELECTROMAGNETIC COUPLING ELEMENTS

EMP energy is coupled to a facility as the result of electromagnetic field interactions with facility conductors and the transfer of energy to sensitive electronic equipment within the facility. The resulting effects on equipment are similar to the effects of other forms of electromagnetic effects such as lightning and EMI.

A simplified layout of a ground based communication facility, Figure 1, indicates various external conductors for power, communications, and grounding that couple the EMP energy to penetrations of the facility structure. These external conductors consist of shielded or unshielded cables, conduit, or single conductors. A microwave relay tower is a major collector and its associated waveguide penetrations carry large currents compared with the buried cable penetrations. The conductor grounding, branching, and the penetration treatment determines the degree to which the external conductors interact with the intra-building cables that connect to sensitive equipment. The intrasite conductors include ac and dc power, signal control, and ground cables. Other conductors such as air conditioning, water and fuel lines may also be important should these other conductors be routed close to cables directly connected to sensitive electronics. The various electronic subsystems within the enclosures vary in susceptibility to upset or damage depending upon the voltage and current levels at the enclosures and the thresholds of the electronic components.

The susceptibility of individual components depends on the upset or damage thresholds of the components, the energy coupled to the components from the facility conductors, and the energy coupled directly to the component from the incident field. The susceptibility of the facility depends, in turn, on the functional relationships between all facility components, and is determined by the facility mission impairments which results from the upset or damage of one or more susceptible components. Experience gained in predicting the responses of the tested facilities indicate that it is possible to identify with good confidence those components which in themselves are susceptible, and which, by virtue of their functional employment in the facility system, are critical from a facility susceptibility standpoint. Their identification can only be accomplished with the aid of preliminary coupling analysis, consideration of building (and component) shielding, determination of component thresholds, and finally, a functional analysis of signal flows through the facility.

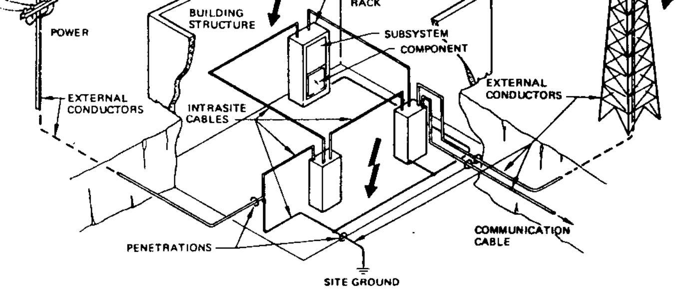

Figure 1. EM Coupling to a Facility

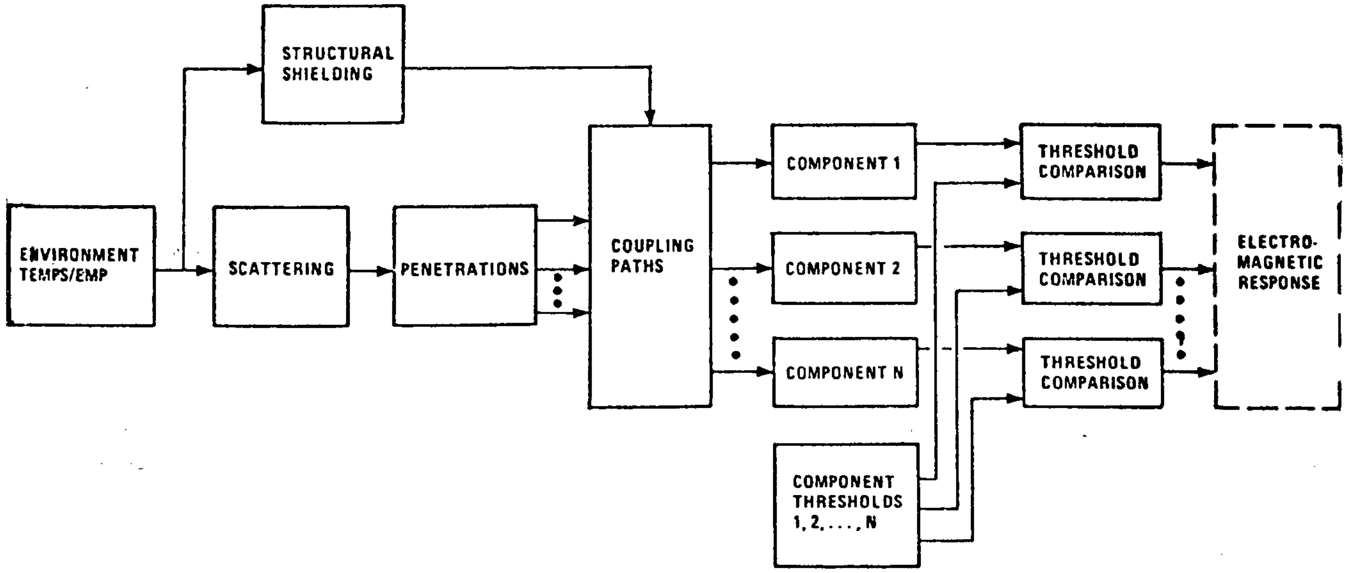

Figure 2. EM Analytical Model

ELECTROMAGNETIC COUPLING RESPONSE MODEL

The EM analytical model utilized to develop EMP functional response predictions is shown in Figure 2. This analytical model includes the energy flow from an external environment, through building scattering and shielding, to coupling and interaction with facility penetrations and intrabuilding cables, and finally, to induced voltage and current waveforms at the components within equipments. These components are selected to be functionally critical and directly relatable to facility functional response. The individual component malfunction probabilities are calculated from the comparison of the EMP induced voltage or current and the characteristic upset and/or damage thresholds of the components, including distribution of thresholds among a family of identical components. The facility functional response parameters are then calculated from a statistical combination of the component responses.

Electromagnetic interaction and coupling between the EMP field and the critical components is determined from a computer solution of detailed electrical equivalent circuits. Code modules for implementing the equivalent circuits consist of subroutines for distributed electromagnetic field coupling to the facility cables and conductors, and code for analysis of the large linear inter-connecting network. The electromagnetic model also includes upset and damage threshold characteristics of the sensitive components. The electrical equivalent circuits, or models, consist of the cable coupling and lumped circuit elements

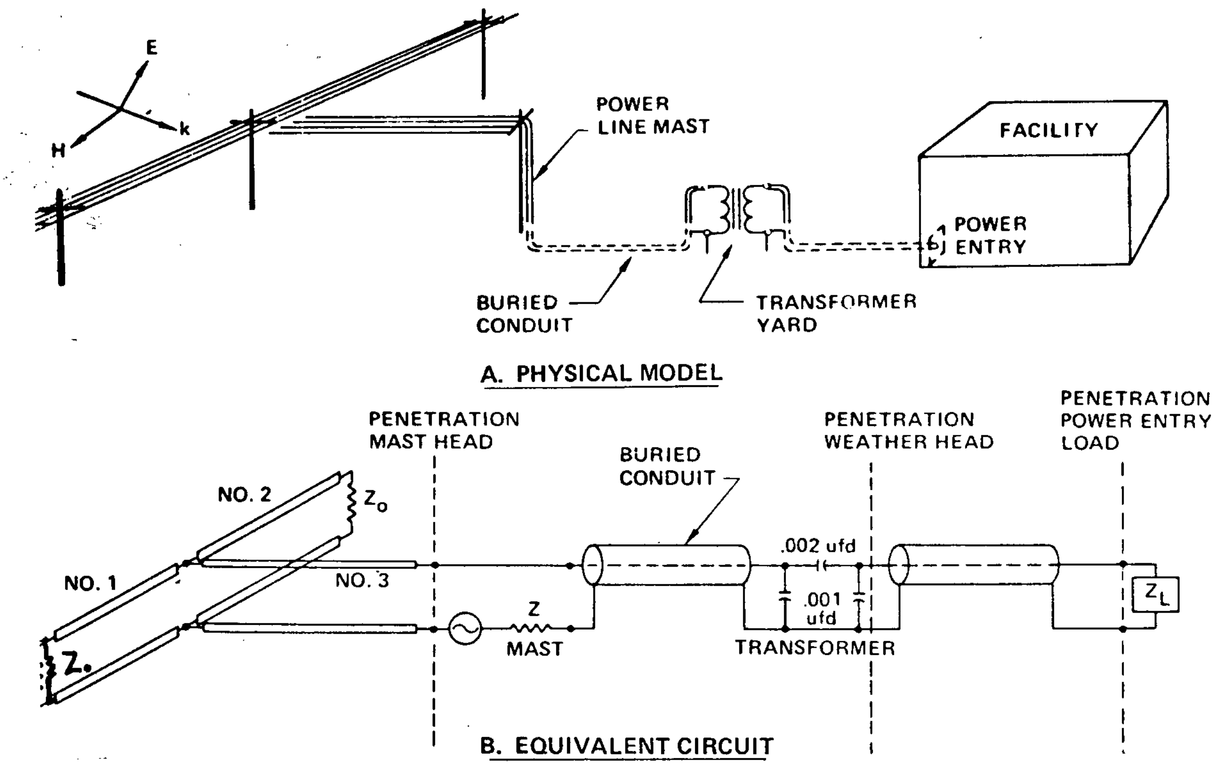

Figure 3. Typical Commercial Power Penetration Path

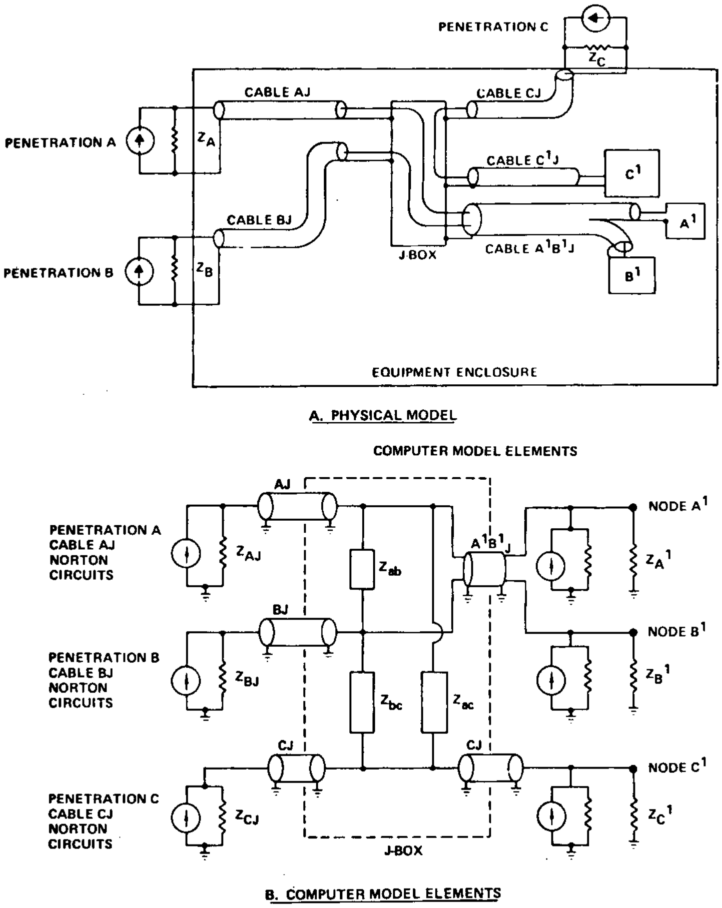

Figure 4. Coupling Path Model

within the site, unique parameters of the site, and the interconnections of these elements to represent the EMP coupling from the external environment to the equipment components. Equivalent circuit models of the external conductors are considerably simpler than the models for the mutually-coupled cables within the building.

The electromagnetic model for the commercial power penetration, although very simple, illustrates the methodology used to model external cables. The physical situation is shown in Figure 3a and the electrical equivalent circuit in Figure 3b. The commercial power lines couple energy from the EMP fields depending upon the electrical characteristics of the earth and the power line height, spacing, and orientation with respect to the EMP fields. The power lines can be represented as electrical transmission lines with common and differential modes. The branch line to the facility consists of another transmission line and a vertical mast. The remaining connections consist of buried metal conduits represented as transmission lines. The solution for the voltages and currents of the equivalent circuit will provide the EMP induced penetration conditions. Since these penetration conditions depend on the impedance of the internal network, the penetration equivalent circuit model is connected to the internal network before computer solution.

As an example of an internal model, the physical configuration in Figure 4a is considered. Here three penetrations interconnect with cables and components through a junction box. The cable shields attach to the junction box and the core wires couple via mutual inductance. The elements for the model of this situation are shown in Figure 4b. The site unique mutual coupling parameters $Z/^{ab}$, $Z/^{ac}$, $Z/^{bc}$ were calculated from the physical layout of the junction box. The internal fields in the building which couple to the cable shields depend upon cable layouts relative to the field orientation. These internal field coupling factors are applied at the ends of the cables as shown in the figure. Component waveforms are determined from computer solution of the internal networks including all the above factors. The only difference between the external and the internal models is the treatment of the building shielding, number of cables, and the resulting complexity of the equivalent circuits.

Many facilities have no provision for attenuating the external EMP fields and the analysis must include consideration of diffusion field coupling directly to the intra-building cables in addition to the penetrations coupling. The internal fields are essentially the same as the external EMP environment for buildings constructed from concrete block, concrete without welded reinforcing steel, or from wood. The degree to which these internal building fields influence the facility response depends upon the amount of unshielded cabling and upon the EMP sensitivity of the electronic components. The internal fields must be considered when the building provides shielding of less than 26 dB in effectiveness.

Typical penetrations and coupling paths are shown in Figure 5. The penetrations, on the left side of the drawing, include the microwave tower, local telephone cable, earth ground, area lights, commercial power, and communication cables. Because of the internal cable connections, the various penetrations are interconnected throughout the intrasite cabling. Sensitive and susceptible components are located in various areas of the facility: the radio alarms; dc power rectifiers; the dc-dc converters for the common control logic and radio equipment, and the signal conditioning equipment in the register-junction path. The sensitive logic and memory components are located in the common control block. Table 1 lists the major code modules and indicates the size of a typical electrical model in terms of: the number of nodes in the network; the number of cables; the number of sources where EMP coupling enters the network; the number of R, L, C, M lumped elements; and the number of loads where waveforms are calculated.

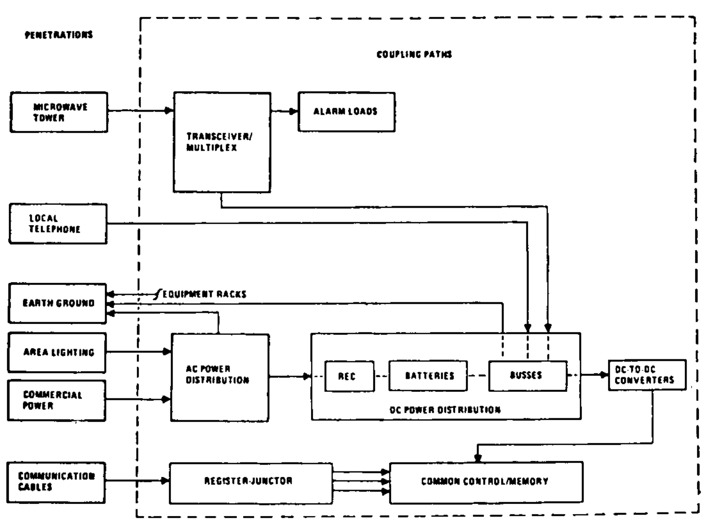

Figure 5. Penetrations and Coupling Paths

Table 1. Typical Code Modules

MODULE	NUMBER OF LOADS	NUMBER OF ELEMENTS	NUMBER OF SOURCES	NUMBER OF CABLES	NUMBER OF NODES
DC DISTRIBUTION	11	146	2	18	208
AC POWER	43	157	36	38	392
COMMON CONTROL	32	1091	35	73	551
REGISTER-JUNCTOR	14	441	28	118	1059

Component responses (probability of upset and probability of damage) are based on disruption calculated at the printed circuit card level of detail and the calculated EMP induced waveforms. Upset and damage malfunctions are considered. The damage analysis involves the determination of the Wunsch constants for the semi-conductors and a circuit analysis from the device terminals to circuit card terminals. Upset analysis is based on the non-linear analysis of the printed circuit card response to transient pulses. Positive and negative pulses are considered and the lowest value is taken as the damage thresholds.

The number of components predicted to be damaged depends upon the distribution of damage threshold levels among nominally identical components, and upon the distribution of the EMP induced levels at the various equipment racks containing the components. The calculation of thresholds and EMP induced levels lead to a probability of damage for the component type.

The PRESTO code incorporates the TRAFFIC numerical analysis processing code to efficiently solve the large electromagnetic models. The numerical solutions are compiled frequency-by-frequency and then numerically transformed to the time-domain. PRESTO also incorporates an interface processor (termed EVALUATE) which allows consideration of the fequency dependent circuit card threshold analyses in the final component response predictions.

The various processors of the PRESTO code are interconnected by an EXECUTIVE code to automate end-to-end computation of: the coupling to the facility conductors; the distribution of the coupled energy through the facility; the induced waveforms at particular components; and the component response. Relating the component response to functional impairments (or functional response parameters) requires a functional model. The development of this model is described in the next section.

Table 2. Functional Matrix

COMPONENT	PARAMETER			
	A	B	C	D
1	P(A/1)	P(B/1)	P(C/1)	P(D/1)
2	P(A/2)	P(B/2)	P(C/2)	P(D/2)
3	P(A/3)	P(B/3)	P(C/3)	P(D/3)
4	P(A/4)	P(B/4)	P(C/4)	P(D/4)
5	P(A/5)	P(B/5)	P(C/5)	P(D/5)

$$P(A) = 1 - \prod_{i=1}^{m} [1 - P(A/C_i) \langle 1 - [1 - P(C_i)]^{n_i} \rangle]$$

FUNCTIONAL RESPONSE MODEL

The functional response model is an algorithm that consists of the probabilistic relationships between component impairment and the functional performance parameters. The functional response model for many communication systems, consists of a matrix which relates an upset or damage of individual components to the various functional response parameters. Table 2 illustrates a generic functional matrix. The probability values indicated are conditional probabilities which define the probability of a functional response parameter given the upset or damage of a specific component. The functional response matrix is utilized by the EVALUATE subroutine of PRESTO to calculate the probabilities of each functional response parameter as indicated by the equation at the bottom of Table 2 where P (C_i) is the probability of upset or damage of critical component C_i. The EMP effects on the communication functions can be described by a set of response parameters. These parameters define the functional behavior of circuits established prior to, during, and subsequent to an EMP event. The response parameters considered sufficient to define communication facility functions are: probability of outage; percent of circuits out of service; probability of improperly processed traffic; probability of misrouting; and probability and duration of delays.

This article is based on a paper prepared by Dr. W. W. Cooley, Dr. D. W. Mahaffey, and Dr. A Rudzitis, of the Boeing Aerospace Company, presented at the 1977 IEEE International EMC symposium. Prepared for ITEM by Walter D. McKerchar of the Boeing Aerospace Co.