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An approach to evaluating and implementing EMP protection requirements for communication centers

H. S. Cabayan
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May 1, 1979

Lawrence Livermore Laboratory

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PREFACE

We performed this work at Lawrence Livermore Laboratory (LLL) in response to the invitation of the Defense Communications Engineering Center, Reston, Va., in the fall of 1977 to look at their EMP hardening problem. This report describes the types of hardening problems encountered during that time for various types of ground communication centers. We believe that most of the concepts in the approach that we developed then are still valid and that the problems of hardening remain an issue of interest in the EMP community in general.

CONTENTS

Preface ii
Abstract 1
Introduction 1
Technical Discussion 1
EMC/EMI Considerations 1
Evaluation of Present EMP Protection Practices 2
Integration of EMP Protection Practices with Non-EMP EM Protection Practices 3
Experimental Evaluation 3
Scale Model Experiments 3
Plates as EMP Energy Reflectors 6
Equipment-Rack Grounding Practices 7
Coupling from Current-Carrying Cables to Adjacent Cables 7
Use of Racks on Cable Currents 8
Effects of Reinforcing Bars (Rebars) 9
Full-Scale Facility Testing 9
Application of Decision Theory to Communication Center Hardening Methodology 11
Summary 14
Acknowledgment 14
References 15

AN APPROACH TO EVALUATING AND IMPLEMENTING EMP PROTECTION REQUIREMENTS FOR COMMUNICATION CENTERS

ABSTRACT

We examine the problem of protecting communication centers against the threat of high-altitude nuclear electromagnetic pulses (EMP). Because such EMP could damage components in an unprotected facility, we describe an approach to develop a set of minimum requirements so that effective hardening procedures can be designed and implemented. Our approach includes evaluation of currently recommended protection practices, cost analyses, and development of test requirements, plans, and facilities.

INTRODUCTION

The operation of many communication-center installations is susceptible to interference from electromagnetic pulses (EMP), and a high-altitude nuclear EMP may sufficiently damage communications equipment that the facility is rendered inoperable. Because of the recognized need to harden these installations against EMP interference, we describe here an approach developed at Lawrence Livermore Laboratory (LLL) to accomplish this goal.

Our approach involves five steps:

- Determine and evaluate the minimum protection currently used in communication centers.
- Evaluate existing protection practices.
- Analyze costs of possible protection practices and determine the most cost-effective alternatives.
- Develop test requirements and test plans for full-scale experimental evaluation of optimum protection practices.
- Incorporate the optimum protection practices into an electromagnetic compatibility and interference (EMC/EMI) program.

In formulating this approach, we assumed that only protection against permanent damage of the communications system was essential and that temporary interruptions could be tolerated as an operational necessity. We also assumed that the equipment was able to withstand those electromagnetic transients encountered during normal operation.

Our approach strives to insure that EMP protection practices can be integrated into current facilities and that they be compatible with present communications equipment. In this report, we discuss available EMC/EMI and EMP protection practices and present a program plan for including EMP protection in an EMC/EMI protection plan. We also describe Decision Theory, which is used for cost analysis (or trade-off) procedures, and describe the full-scale developmental facility testing used to validate the results of scale-model tests.

TECHNICAL DISCUSSION

EMC/EMI CONSIDERATIONS

Any approach to the hardening of communications facilities to EMP must consider the existing EMC/EMI requirements and should be combined with an EMC plan. These requirements include:

- Compatibility with protection against other electromagnetic (EM) effects (e.g., lightning).

- Immunity to out-of-line radiation or coupling.
- Immunity to in-line noise.
- Compatibility with equipment during normal operation.

Specification of EMP requirements generally should not conflict with other EMI considerations (with the possible exception of lightning protection). Certain types of equipment may have to meet MIL STD 461 and Secure Communications requirements. On the equipment interface level, however, it appears that a suitable transient requirement for both lightning and EMP surges can be imposed.

The Department of Defense (DOD) has established an integrated Electromagnetic Compatibility Program[1] to establish EMC requirements for all military equipment, systems, and subsystems. The objectives of this program are:

- To achieve EMC of all equipment.
- To incorporate this compatibility at the design stage (avoid retro-fitting).
- To standardize approaches and techniques in communication electronics materiel programs.

Criteria for establishing, managing, and evaluating an EMC program for communication equipment is provided by MIL-HDBK-237, and mandatory requirements for such equipment are described in military standards and specifications. None of these specifications considers EMP, however, and the tests they describe are performed over selected bandwidths (typically in a continuous narrow- or wide-band wave) whereas EMP involves transient phenomena.

EVALUATION OF PRESENT EMP PROTECTION PRACTICES

The crucial task facing a system designer is determining which of the practices recommended to control nuclear EMP interference[2–7] can be implemented in the most cost-effective manner. These practices fall into several categories:

Protection of the communications facility.
- Shielding of buildings.
- Grounding of equipment.
- Filtering of power lines.
- Limiting of transients on telephone lines.
- Treatment (e.g., shielding, grounding, bonding, filtering) of "penetrations" (i.e., any material that conducts electricity, such as wires, cables, pipes, etc.) that pass through building shielding.

Protection of the communications equipment.

Intersystem protection.
- Shielding and spacing of equipment racks.
- Shielding and spacing of equipment cables.
- Grounding of equipment.
- Isolation and zoning of equipment.
- Circuit layout practices.
- Signal transmission methods (e.g., microwave, cable).

Intrasystem protection.
- Layout of interconnections.
- Bonding, grounding, and shielding of interconnections.
- Terminal connections protection.
- Signal level amplitudes.
- Nature of signal transmission (e.g., digital, optical).

The system designer evaluates the implementation of these practices separately using several criteria:

Survivability. Survivability is a measure of the system performance under extraordinary circumstances. Assessment of survival factors depends both on intricate technical considerations and experienced judgment (because these factors cannot yet be measured instrumentally). This measure can contain significant uncertainty as a result. The degree of uncertainty of such estimates can be expressed in several ways. One method (based on reliability theory) associates with the survival factor a statistical confidence factor that incorporates an empirically determined distribution of uncertainty. If this confidence factor is not sufficiently high, however, the final analysis of survivability will contain so much uncertainty that no decision can be made.

Component Failure. The reliability of protection devices under stress must be considered, e.g., the failure rate of Zener diodes used for transient suppression.

Cost. Cost includes both installation and maintenance costs. Some protection practices, though attractive from a technical point of view, may be prohibitively expensive, e.g., shielding the entire facility.

Space Requirements. The protection method can not require excessive installation space, e.g., shielding of individual conductors in cables.

Structural Integrity and Safety of Personnel. The method must not compromise the structural integrity of the buildings or electrical safety, e.g., although a ground wire may produce EMP interference, it is required for safety and must be retained.

Communication installations are categorized as three different types of structures, each of which has a different level of EMP shielding. These categories are:

Well-shielded facilities.

- Structures are steel or steel-containing (steel walls, floors, and ceilings) with a limited number of apertures (i.e., doors, windows, cracks).
- EM fields inside structure are unaffected by external EM fields.
- Penetrations constitute the major source of EM fields.

Less-shielded facilities.

- Structures are steel-frame or rebar-reinforced with numerous apertures.
- EM fields inside structure are considerably affected by external EM fields; EMP interacts with both the structure frame and interior metal fixtures (cabinets, racks, cables, etc.).
- Penetrations contribute considerable EM fields and coupling from the outside.

Unshielded facilities

- Structures are wooden- or concrete-frame (little metal in walls, floors, or ceilings) with numerous apertures.
- Equipment and outside EM fields interact directly.
- Penetrations add considerably to the EM fields inside the structure.

INTEGRATION OF EMP PROTECTION PRACTICES WITH NON-EMP EM PROTECTION PRACTICES

The EMC control plan is a source for all EMC technical information for designing systems to control EMI phenomena and should include EMP protection when such is applicable. The plan determines how the combined problems of EMP and other EMI effects are to be solved.

An EMC control plan includes both administrative and technical sections that should contain the following:

Administrative

- Plan, scope, and description of system.
- Organization, coordination, and reporting procedures.
- Applicable documents.
- Milestones.
- Documentation and schedule.

Technical.

- Engineering activities.
- EMC design criteria (bonding, grounding, shielding, cabling).
- Prediction of problem areas.
- Testing provisions.

Figure 1 indicates how and where data and requirements for EMP enter into and interface with the EMC Program and Control plan and other documents. The decision process interacts with the other functions (design reviews, control-plan generation, tests); only the design review is emphasized in the figure.

Some work in the field of EMP protection and hardening that is specifically oriented to communication facilities has been reported.[2–7]

EXPERIMENTAL EVALUATION

SCALE MODEL EXPERIMENTS

The EMP-induced effects on any electronic system ultimately appear as voltages and currents (and their associated fields) on cables, metal surfaces, and other conductors. At present, the external coupling problem, which involves the interaction of incident EMP with directly exposed parts of the system, is reasonably well understood. The penetration of externally coupled energy to the system's interior (e.g., through apertures) is less understood.

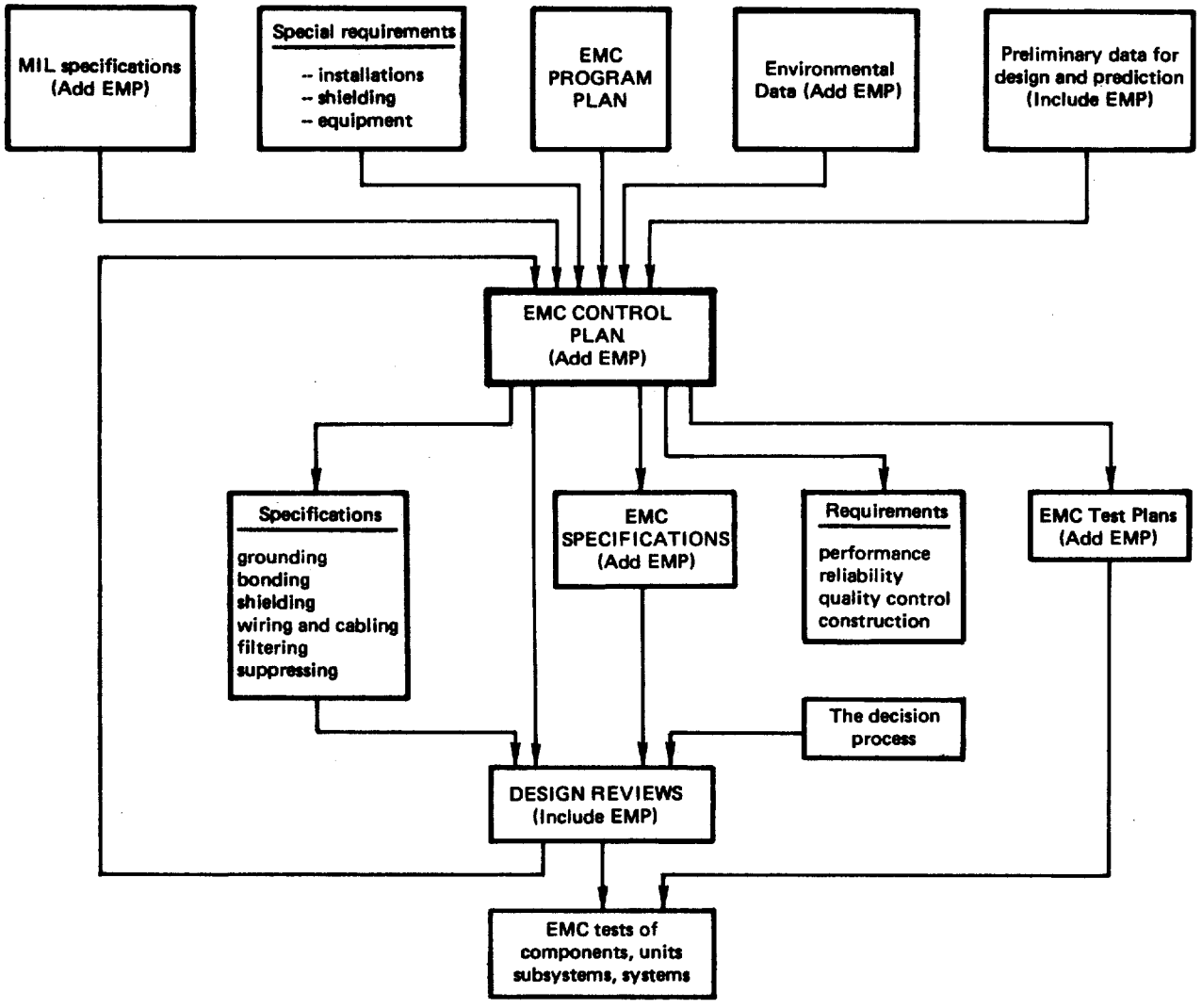

FIG. 1. Relationships between documents and functions in a typical EMC program. This diagram shows location of decision points and also indicates where EMP considerations should be included in the EMC program.

Of greatest uncertainty, however, is the redistribution of this energy in the interior of the system. We feel that properly designed scale-model experiments can help solve this latter problem.

Scale model tests offer several advantages:

- They help evaluate design practices.
- They complement analysis- and full-scale experiments.
- They are relatively inexpensive.
- They provide well-defined control experiments.
- They permit design of definitive, productive full-scale experiments.
- They minimize the number and cost of full-scale experiments.

One disadvantage of small-scale experiments is the uncertainty that their results can be validly applied to actual full-scale measurements. At LLL, we performed experiments using models of physically large structures (e.g., ships, missiles, land-based vehicles) in which we measured external coupling to communication equipment in these vehicles. We used monographs of a set of EMP data modules[8] developed for Defense Nuclear Agency (DNA) at LLL, and, within about an hour, we obtained predictions that were within 3 dB of actual field test results.

In these experiments, we used scale models. Scale models (simulators) do not simply act as analogs to the "real" objects (simulands), but instead are distinct physical systems that differ only geometrically from the simuland. These models are

valid if we view the simuland as an interconnection of points; the scale model differs only in the individual dimensions and representations of details of the parts because the physical structure and material compositions in both systems are the same.

In testing the effects of electromagnetic radiation on complex electronic equipment, we use scale experimentation to estimate the probability of successful system operation. When a large class of systems is considered, two fundamental problems become apparent: choosing the correct experimental design and validating the experimental results.

Scale-model experiments must be very carefully designed to exploit the available information to the fullest. From a potentially infinite set of stimulus-response observations, the experimenter must select an economically finite set that is based on sensitivity of the system response, internal geometric rearrangements, subsystem coupling, functional nature of subsystems, etc. Such information can rarely be expressed correctly in purely quantitative terms.

Scale-model experimental results must be very carefully validated with respect to the simuland. Not only does this require carefully designed experiments on a real system that is likely to be inaccessible, but the ability to interpret model data with respect to the simuland requires significant expertise in EM scaling theory.

A basic hypothesis of our approach is that a "generic" building can, by suitable rearrangement of its internal parts, serve as a sufficiently good model of any real building. To set up a scale experiment, the designer divides the modeling problem into two portions—the scaled portion that deals with scale models and the portion that deals with models of real systems. At the lowest level of the real world are the most detailed simulands, and, in moving up the hierarchy of simulands, the degree of detail decreases as the simulands are grouped in increasingly more general aggregates. For example, in a study of the vulnerability of buildings to EM radiation, individual buildings, S, comprise the first level and the "real size" facility (made up of several buildings) comprises the second level. In such a two-level heirarchy, the second level represents a generic system, S_P, where P is a parameter determined empirically to obtain a sufficiently good approximation of the individuals in the system. In our example, this parameter would describe the different internal rearrangements of equipment required in the generic building to model a specific building in the lower level.

Figure 2 shows such a multi-level approach to the problem; we subject a real-world system S to an EM energy U, and Y, a function of the stimulus U [i.e., Y = S(U)], is the resulting probability distribution of measurements taken during the experiment. In the scaled world, experiments are conducted with a scale model of the generic system, $S_{P'}$, with the corresponding inputs (U′), outputs (Y′), and parameters (P′). For a model arrangement, an output Y′(P′, U′, L′) is obtained at sensor location L′. When P′, U′, and L′ are varied randomly, Y has a distribution function f_Y, as shown in Fig. 3. Unless the experiments are designed and categorized judiciously, the distribution variance is prohibitively large.

Two essential issues affect the correlation between sensors and unrelated structural features in the tested system (facility). First, equivalent experimental arrangements (layouts) must be identified to avoid duplication of experiments. Second, the response function Y(P, U, L) must be assigned a

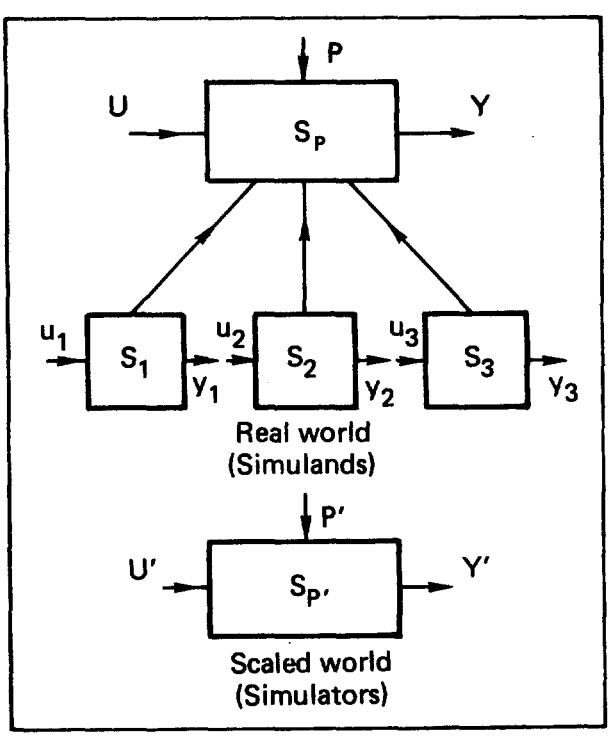

FIG. 2. A scale model approach to the hardening problem. In the real-world system, Y is the probability distribution resulting from many EM stimuli (U) that are affected by parameters P. In the scaled world, the input and output are simplified.

parameter C (a "clutter" factor) to account explicitly for the varying sensitivity of Y(P, U, L) to different layouts. The clutter factor, included in P, combines equivalent layouts and indexes Y to produce a collection of Y distributions—one for each significant layout.

The distribution in Fig. 3 represents an aggregation of all arrangements and normally shows a very high variance. Figure 4 shows the effect of introducing a clutter factor, C. The use of this factor reduces the uncertainty of the data by separating the structural aspects of the system (e.g., a building) that are responsible for the wide variance usually obtained. Each value of C is then associated with a response distribution function of lower variance than Y. Using C is computationally and experimentally efficient, but these advantages are offset in that we must deal with a collection of distribution functions, one for each value of C.

There are essentially three sources of uncertainty associated with determining the EMP-induced threat in the interior of an electronic system. These are variations in 1) the externally incident EMP (its angle of incidence, polarization, frequency spectrum), 2) the system configuration (its geometry, electrical interconnections, operational status), and 3) the location of the observation point on the system. These variations produce EMP-induced interference-signal ("threat") distributions that must be considered when making vulnerability assessments, but in practice these distributions generally cannot be obtained from full-scale measurements with any degree of completeness. Scale-model experiments can help resolve this problem in at least two ways: first, they provide a well-defined controlled environment in which threat distribution functions can be determined readily, and second, they aid in the efficient design of the full-scale experiments that are required to validate the scale-model results.

Specifically, scale measurements of the excitation applied, the interior configuration of the model, and the interior measurement points are performed using pulsed sources to cover the wide bandwidth of EMP-coupled energy. This provides consistent input of energy whereby all energy delivered to the interior of the model can be accounted for. These experiments, conducted adaptively in a learning mode, reveal the relative effects of such parameters as the degree of interior filling, importance of nearby walls and corners, internal resonance, and coupling models on the effects of EMP.

Plates as EMP Energy Reflectors

Entrance panel plates to which penetrating cables are bonded can serve as good energy reflectors in cinder-block buildings for which the outer building shield cannot be used for grounding. In the scale model of this situation, we mounted a 3-m long wire 21 cm above the ground plane (Fig. 5); at one end was a 50-Ω load. We first measured the voltage induced across the load when we generated a current pulse at the other end of the wire. We then installed a 21-cm-diam reflecting plate about 1.7 m from the load end and again measured the induced voltage across the load. Figure 6 shows the time histories of the measured voltage pulses. From the voltage waveshapes, we deduced that the introduction of the plate reduced the energy delivered to the load by a factor of 2.3.

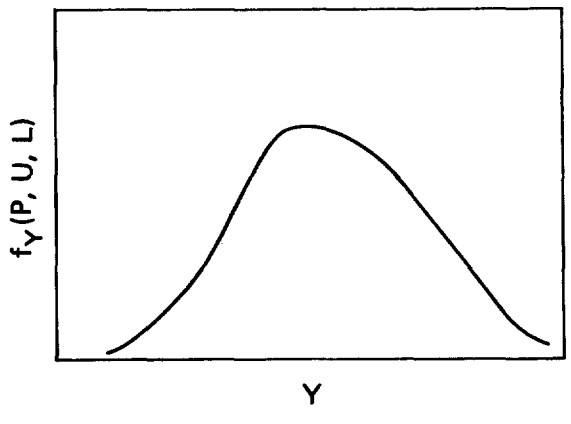

FIG. 3. Typical sensor-output probability distribution.

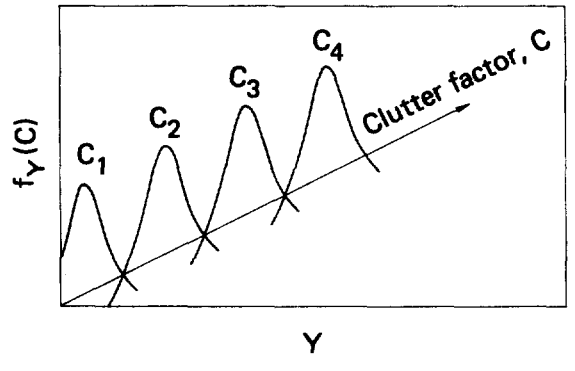

FIG. 4. Effect of introducing a clutter factor (C). This factor reduces the uncertainty of the data obtained when a facility is subjected to EM stimuli.

Figure 7 shows the ratio of induced voltage (with:without the plate) as a function of frequency. The peak voltage was reduced by a factor of three; furthermore, the plate appeared to act as a filter for rejection of frequencies between 0.3 and 1.1 GHz, attenuating them by a factor of two.

Equipment-Rack Grounding Practices

This experiment evaluated the degree of protection from conduction currents obtained by the grounding of equipment racks. To simulate racks, we constructed model racks (8 by 19 by 30 cm) from copper screen, and to simulate incoming cables, we used metal wires 20 cm above the floor to connect the racks to an impulse generator (Fig. 8). Current was measured at the grounding connection to the racks.

We studied three grounding configurations:

Case 1. No grounding; racks were insulated from the ground.

Case 2. Low resistance grounding; racks were connected to grounding plane using wires.

Case 3. High resistance grounding; racks were connected to grounding plane through a 100-Ω resistor.

We observed no appreciable differences in the peak amplitudes or damping constants of the responses for the three grounding configurations. Figure 9 shows the response for Case 1. The capacitive coupling between the racks and ground was sufficiently large that the resistive load in Case 3 did not act as an efficient energy absorber.

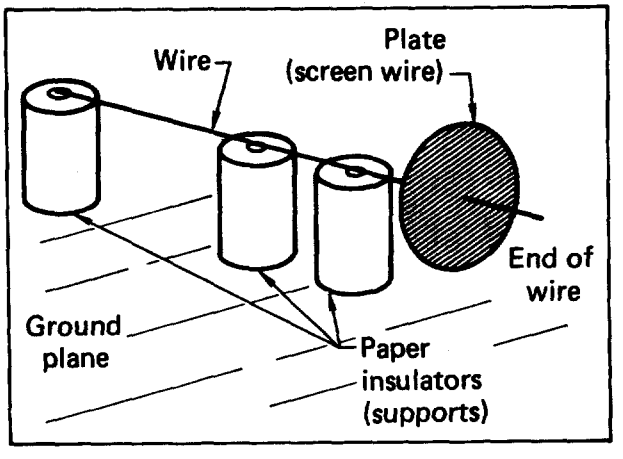

FIG. 5. Model of the situation in which penetrating cables are bonded to entrance panel plates.

Coupling from Current-Carrying Cables to Adjacent Cables

This scale model studied coupling between intrasystem cables and nearby conductors that carry large amounts of current to sensitive components.

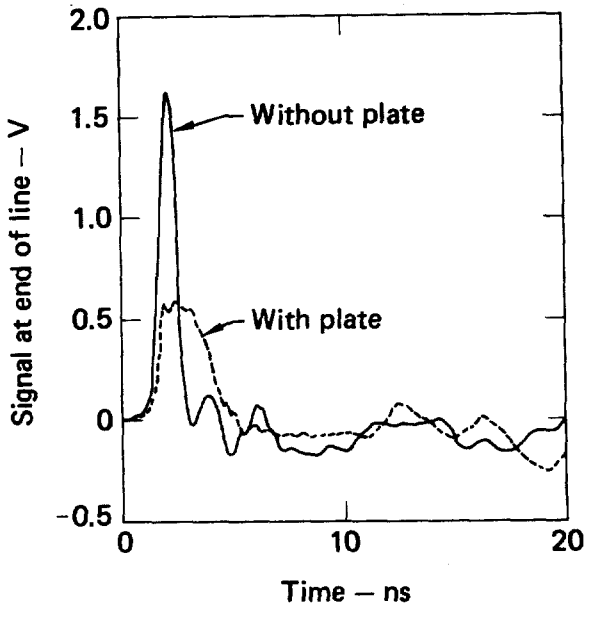

FIG. 6. Time histories of voltage pulses across 50-Ω load measured with and without the entrance panel plate in the model shown in Fig. 5.

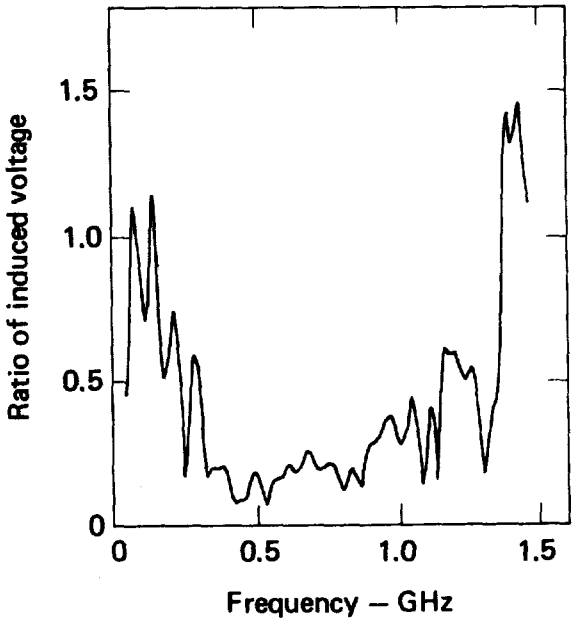

FIG. 7. Ratio of induced voltage (with:without plate) across 50-Ω load as a function of frequency; data were taken from the model shown in Fig. 5.

This coupling represents one of the major paths for energy flow from these conductors.

In evaluating this type of coupling, we were interested in both peak amplitudes and frequency content. We designed two experiments. In each experiment, we generated the current pulse shown in Fig. 10 in a relatively long wire (C_1) mounted 30 cm above the ground.

In Case 1, we positioned a 35-cm-long wire (C_2) parallel to and 10 cm away from C_1 and at the same height above ground; C_2 was grounded at one end and terminated with a 50-Ω resistor at the other. The effective coupling length between C_1 and C_2 was thus 35 cm. In Case 2, we positioned racks under the driven cable as shown in Fig. 11. Figures 12 and 13 show the current that existed in the load resistance of C_2 before and after the racks were put in place, respectively.

We observed that the racks reduced the coupling between the wires by one-half. We also found that the induced current in C_2 exhibited oscillations not present in the driver current and that the width of a burst of these oscillations exceeded the driver-pulse width. Observation of the oscillatory nature and frequency of these induced signals indicated that capacitance effects appreciably coupled intermediate frequency components but that circuit inductance limited the efficient coupling of high-frequency components.

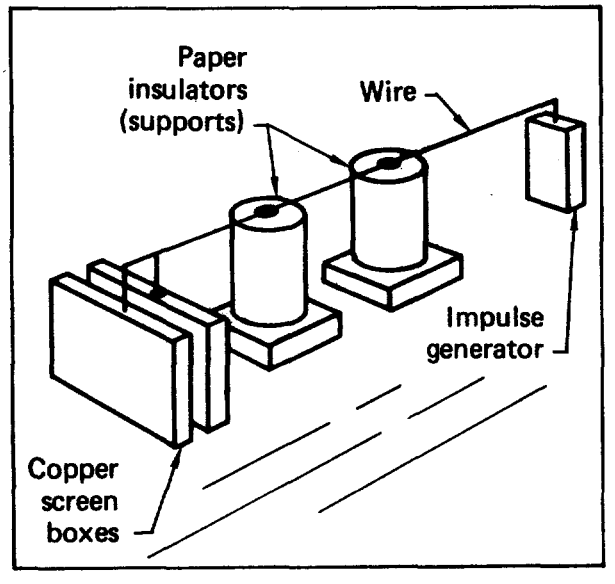

FIG. 8. Model of different configurations of incoming intrasite cables and equipment racks.

Use of Racks on Cable Currents

This experiment evaluated the effects of racks on currents induced in cables. We positioned a wire between two racks to simulate cables running in cable trays. We then added one to seven racks in different positions and, using a current probe,

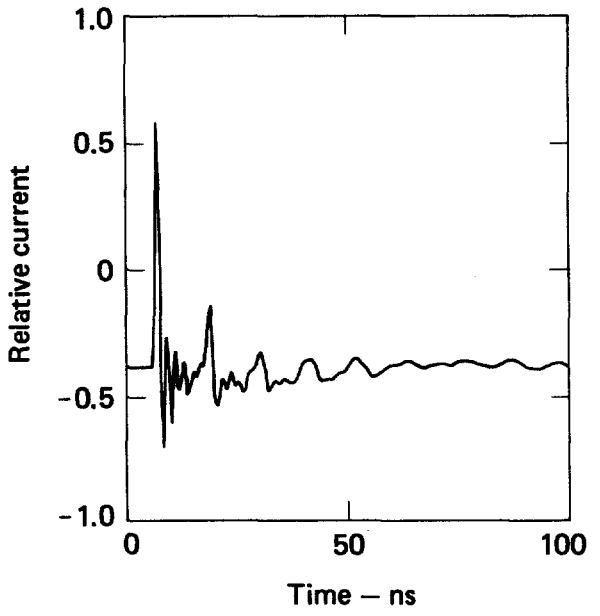

FIG. 9. Current responses for grounding configuration of Case 1; data were taken from the model shown in Fig. 8.

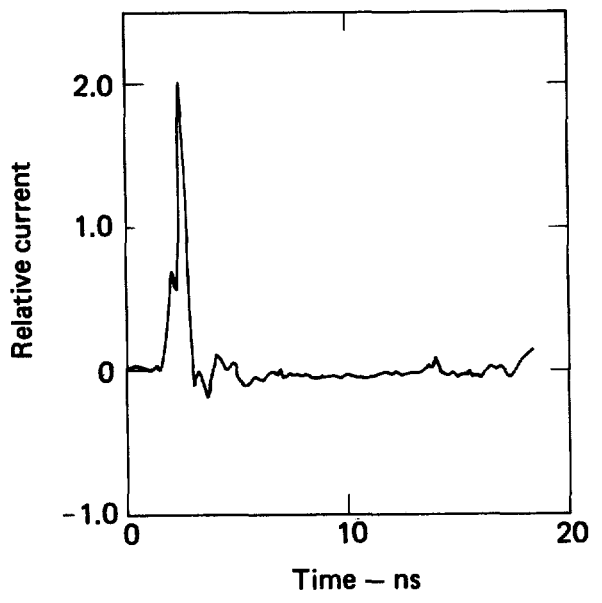

FIG. 10. Current pulse on current-carrying conductor.

measured the current induced in the wire as the apparatus was illuminated with an EMP of 1 kV/m peak amplitude, 100 ps rise time, and 300 ps pulse width.

Figure 14 shows the experimental arrangement in which seven additional racks were used, and Fig. 15 shows the measured response for this set-up. We were surprised to observe only slight changes in peak amplitudes, frequency content, and damping constraints for all the different numbers of racks and configurations; we had expected that using more racks would decrease the induced current.

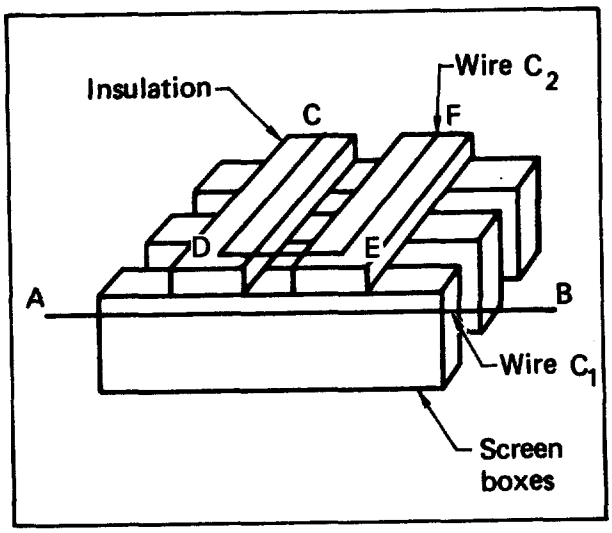

FIG. 11. Model to study coupling between cables and nearby conductors.

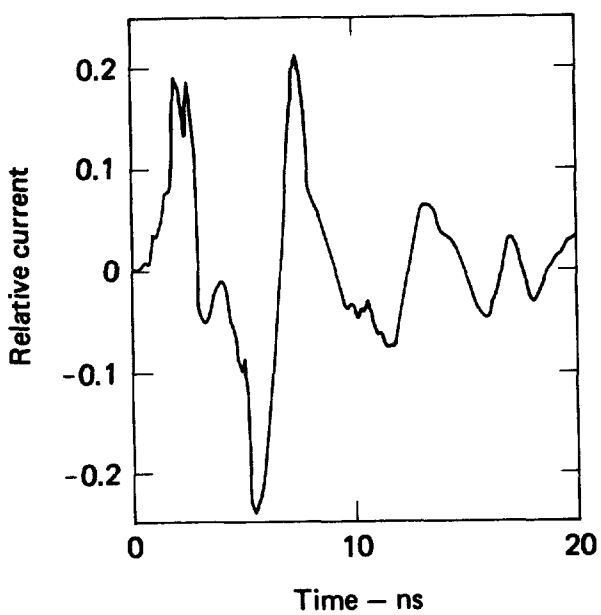

FIG. 12. Induced current in nearby cable without racks (Case 1).

Effects of Reinforcing Bars (Rebars)

In this simple model experiment, we studied the effects of the vertical rebars used in communication facilities to reduce interior field amplitudes and energies. We placed small 30-cm-long metal rods around a 30 by 40-cm area at 5 cm intervals so that they did not touch the ground plane (Fig. 16). We illuminated the set-up with an incident vertically polarized plane wave (1 kV/m peak amplitude, 100 ps rise time, and 300 ps pulse width) and measured the induced E and H fields with $\dot{B}$ and $\dot{D}$ sensors, respectively. Figures 17 and 18 show the measured fields before and after the rebar structure was introduced. We observed that introduction of the rebar structure reduced the peak amplitude of the E and H fields by nearly half. However, the rebar structures are good collectors of energy and maintain the internal oscillatory fields over a long period of time. A preliminary calculation showed that the total energies delivered to 50-Ω loads were about the same with and without the rebar structure—an interesting and unsuspected result.

FULL-SCALE FACILITY TESTING

There are three test levels for evaluating the effectiveness of protection and hardening programs: full-scale full-threat (FSFT), specialized full scale [less than FSFT or direct injection at specific points of entry (POE)], and scale model tests. Although a

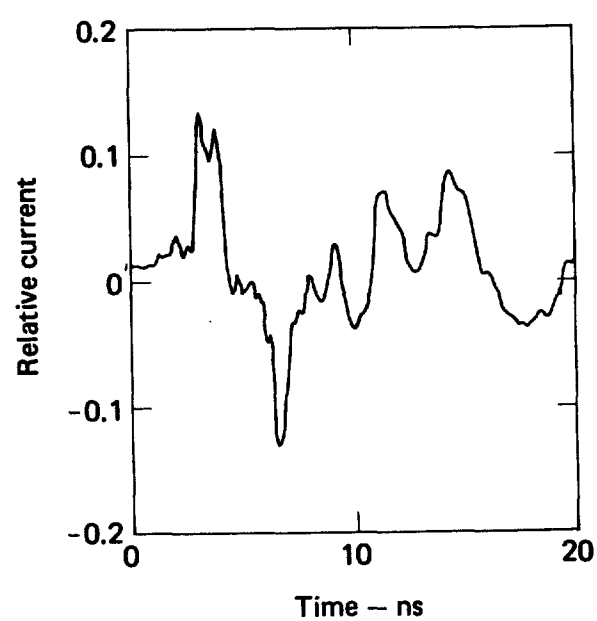

FIG. 13. Induced current in nearby cable with racks (Case 2).

FSFT test would be appropriate to evaluate an equipped communication facility of reasonable size, it would be very costly and would be used only as a validation exercise at some late point in the hardening program. Furthermore, a FSFT test would not contribute much to the development of engineering practices. Scale model tests have proven more useful in this respect, and we discussed the benefits and limitations of such scale model tests in an earlier section.

The alternative to FSFT testing is a program of specialized full-scale tests that combines analytical modeling with scaled-down tests. Such tests are performed on a full-scale object, e.g., a "typical" communications facility. This multi-experiment developmental facility represents structures enclosing communications equipment and is constructed to incorporate different EMP protection practices. Although a full complement of communication equipment is not necessarily required, the layout, distribution, and termination of cables mimics that used in the real world, and most, if not all, of the main power system is included.

Testing is performed using an EMP simulator, direct injection, and other tests specifically designed to gather engineering design information. For example, because the technical features of external coupling of EMP to the simpler geometrical configurations are reasonably well understood, the nature of the EMP-induced signals are also predictable for worst-case situations. Therefore, the effectiveness of hardening measures incorporated in the experimental facility can be tested by directly injecting the EMP signal at each penetrating element and measuring the indirect coupling to circuits or equipment inside. The results are then used to validate predictions made using scale models.

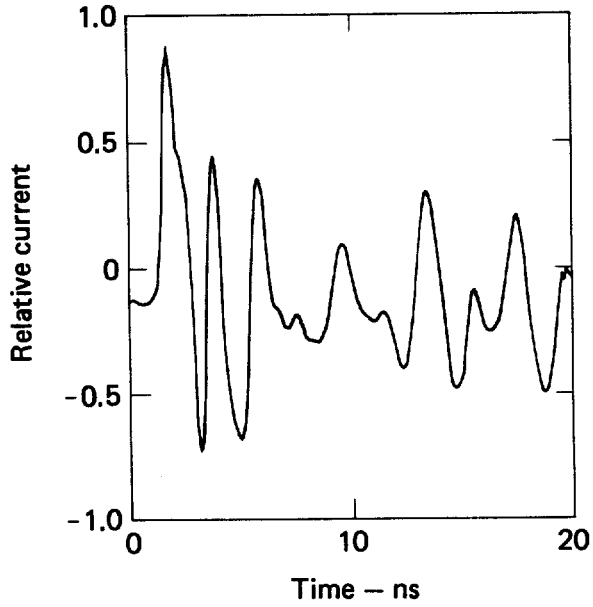

FIG. 15. Induced response in cable for the experimental arrangement in Fig. 14.

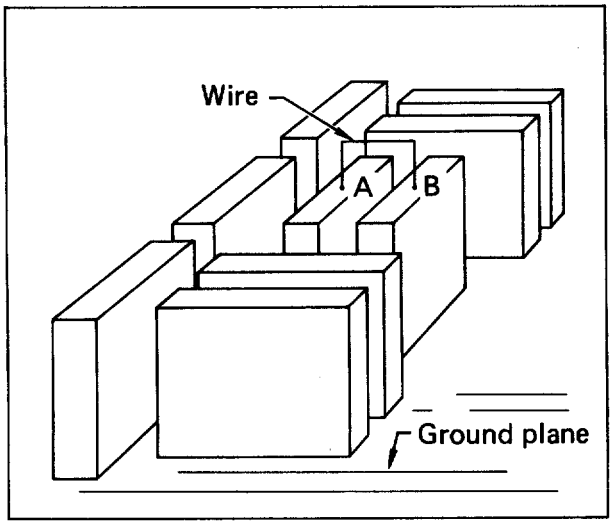

FIG. 14. Model to evaluate effects of racks on currents induced in cables. In this case, the experiment included seven additional racks.

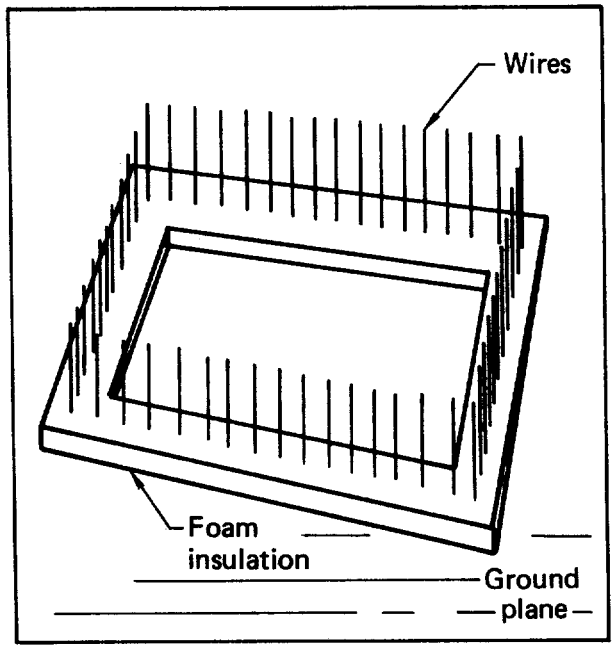

FIG. 16. Model to study effects of the vertical rebars used to reduce internal field amplitudes and energies.

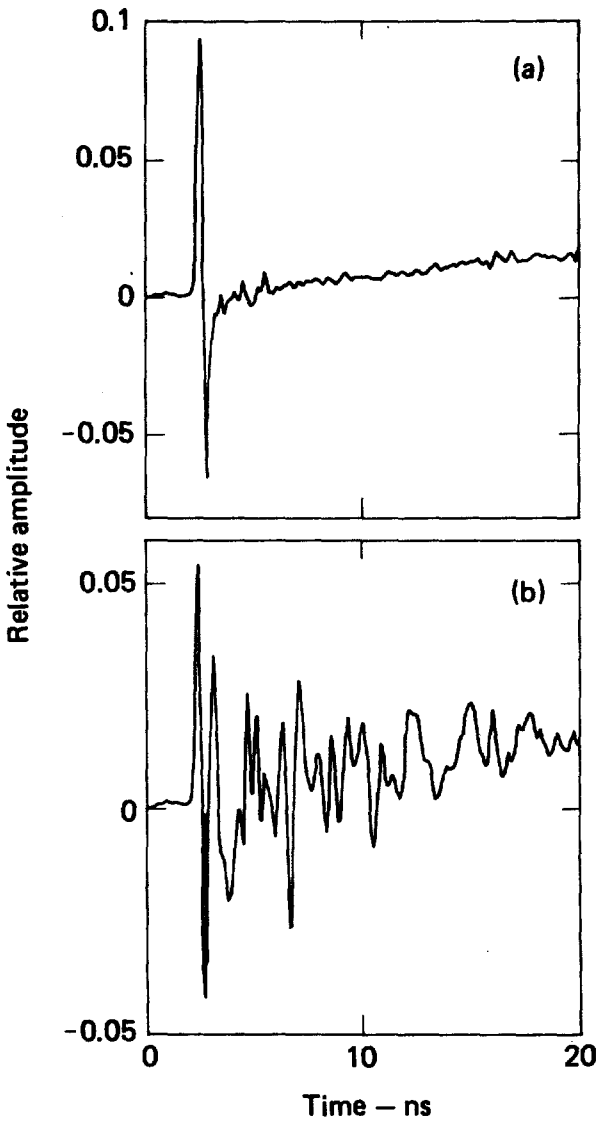

FIG. 17. Ambient E-field measured with a $\dot{D}$ probe (a) without and (b) with rebar structure present.

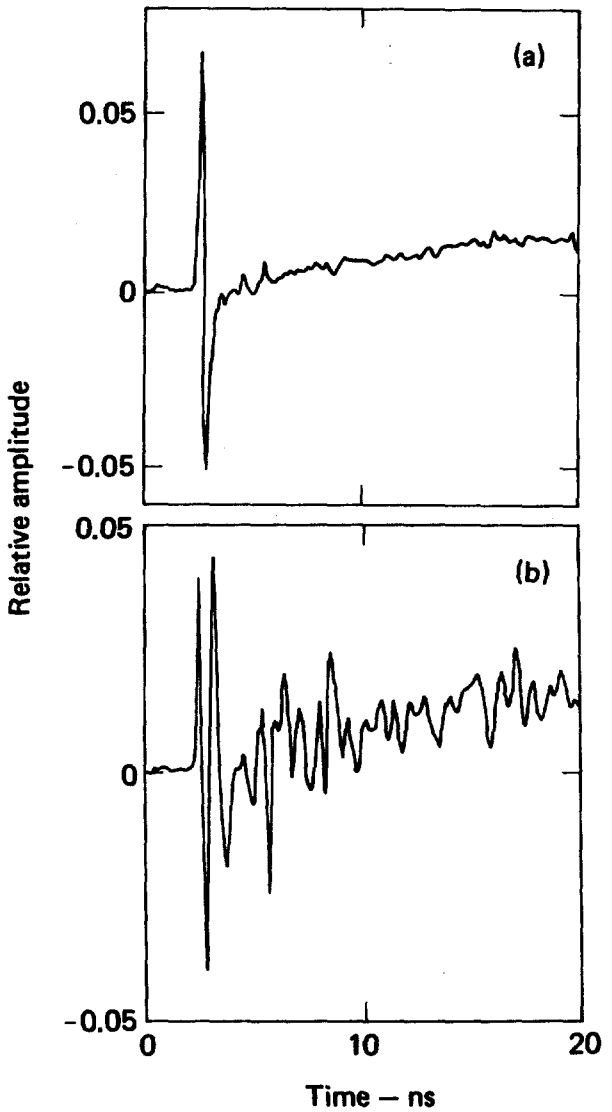

FIG. 18. Ambient H-field measured with a $\dot{B}$ probe (a) without and (b) with rebar structure present.

APPLICATION OF DECISION THEORY TO COMMUNICATION CENTER HARDENING METHODOLOGY

We describe here a methodology for selecting optimum sets of practices to harden communication facilities against EMP. We developed this approach using Decision Theory,[9-12] a discipline that evaluates alternative actions systematically and allows a choice of actions that maximize a desired benefit.

Utility is one basis for selection. Utility assessment (the process of weighing the pros and cons of a prospective course of action) includes the following steps:

- Identify the organization that issues the standards.
- Identify the decision objectives to be achieved. In this case, an appropriate goal is "proper" operation of a communication facility in a nuclear EMP environment.
- Identify a set of alternatives.
- Identify a set of attributes or preference measures. These attributes determine the degree to

which alternative courses of action meet the objectives by indicating the consequences of these actions. Because some consequences are desirable and others are not, these multidimensional measures help make a selection possible when trade-off questions arise. In our case, for example, attributes include the survivability of the system and the cost of the protection.

- Establish a preference for certain consequences. This ordering is usually achieved by use of a utility function with each consequence.
- Develop operation measures for each attribute. For example, for survivability (s), this may be $0 \leq s \leq 100\%$; for cost (c), $0 \leq c \leq \$10M$; etc.
- Choose an assessment technique for the utility or benefit of each attribute. This step converts the physical measure into a utility measure, e.g., functions such as $u_s(s)$, $u_c(c)$, etc. (see below), and uses a scale of 0–100.
- Choose an assessment model. For example, we use an additive model in which $u_t = w_s\, u_s(s) + w_c u_c(c) \ldots w_x u_x(x)$, where u_t is the total utility and w_x is the weight attributed to each utility factor. The most important attribute (e.g., survivability) is given the largest weight, etc. If survivability is the only attribute, $w_s = 1$ and all $w_x = 0$; this is a simple problem, assuming that $u_s(s)$ increases monotonically with s. A system designer must usually also consider budgetary and other constraints in nearly all situations, however.
- Maximize the total utility.

Absolute determination of survivability causes difficulties in evaluating the impact of implementation of a given practice. This impact may be described in terms of a probability-density distribution of survivability outcomes. The uncertainty arises from several sources:

The uncertainty of the state of the system; communication facilities are highly complex and not easily modeled in electrical terms.

The uncertainty of the analysis.

The uncertainty of the degree to which the practice has been implemented. Any practice is subject to interpretation by technical personnel who perform the work, and the system design may not correspond completely to that used in the field. Physical and spatial restrictions may also prevent 100% implementation. Implementation uncertainties for simple practices (e.g., shielding all intrasite cables) is small, but more complex practices (e.g., locating internal signal cables at least 3 m from penetration cables whenever possible) lead to some interpretation by production or installation personnel.

Given a type of facility and the communication equipment it houses, the system designer is faced with determining the best combination of 1) EMP protection for the facility itself and 2) equipment that can be protected to a specified level within cost restrictions. Each facility may require a different combination from the set of optimal practices.

Decision Theory provides a structured and systematic approach for selecting the optimal set of practices and helps the system designer to avoid the pitfalls of other assessment programs. It identifies those areas that require further technical work; in cases in which such technical gaps have minimal impact on the final protection goals, Decision Theory indicates that further technical work is not necessary. Using a systematic method to evaluate the dependence and sensitivity of the ultimate outcome of assumptions, initial conditions, and predictions on protection practices also simplifies the task of determining the minimum accuracy required of these factors. Because the literature on Decision Theory adequately describes several procedures for assessing utility functions,[9–11] we do not discuss them here. Determination of the importance weights, which addresses the important issue of attribute weighting, is also sufficiently covered in the literature.

To illustrate the evaluation procedure, we consider an evaluation involving two attributes: survivability (s) and cost (c). In this context, c includes implementation, maintenance, and projected costs. We can total these projected outlays by use of the net present value of future monetary outlays:

$$c = \sum_{t=0}^{t} \lambda^t c_t \ ,$$

where c_t represents the net flow (in dollars) after t years and λ is an appropriate discount factor that weights future outlays of money.

Figure 19a shows an example of the dependence of the survivability utility function, $u_1(s)$, on survivability (s). By definition, the utility of $s = 0$ is 0 and that of $s = 1$ is 100. According to this example, if $s < 0.4$, the survivability value is low, which indicates that introducing this level of protection provides insignificant utility. Above 0.4, the survivability value increases rapidly with increasing s

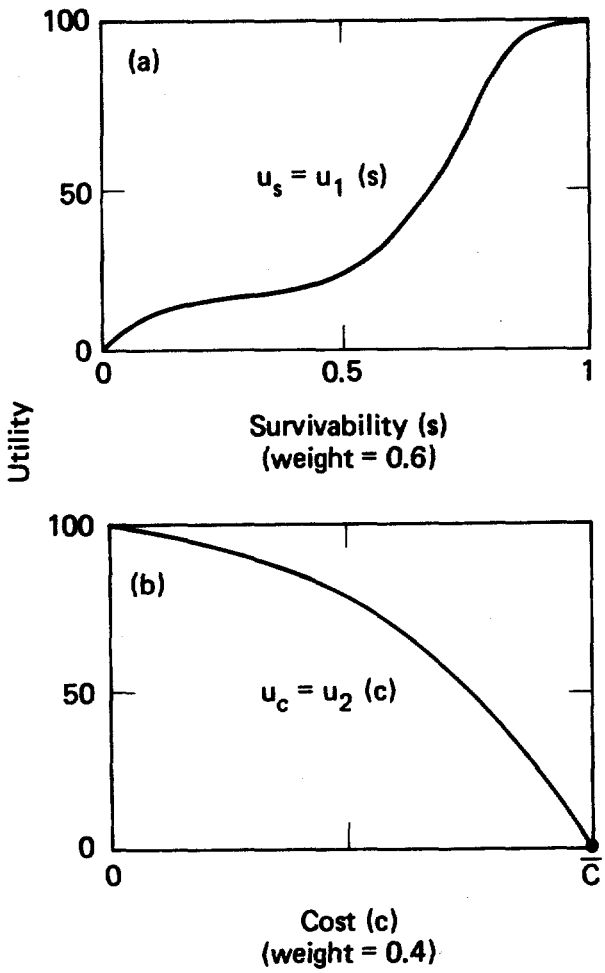

FIG. 19. (a) Dependence of the survivability utility function, $u_1(s)$, on survivability (s). (b) Dependence of the cost utility function, $u_1(c)$, on cost (c).

until the point of diminishing returns is reached at s = 0.8 where the utility curve levels off.

Figure 19b shows an example of the dependence of the cost utility function, $u_1(c)$, on cost (c). The cost ranges from 0 to $\bar{c}$, where $\bar{c}$ is the budgetary limit imposed on the hardening program. We assumed that $u_1(c)$ decreased monotonically as c increased. In this work, we arbitrarily assigned a weight of 0.6 to $u_1(s)$ and 0.4 to $u_2(c)$.

One possible set of objectives for this simplified exercise could be to maximize survivability and minimize cost. Once s and c have been determined, the total utility function (u_t) is calculated from the relation

$$u_t(s,c) = 0.6u_1(s) + 0.4\,u_2(c)\ , \qquad (1)$$

where u_t, u_1, and u_2 are scaled from 0 to 100.

For simplicity, we assume that the system designer can choose between only two sets of practices, p_1 and p_2; p_1 and p_2 need not be mutually exclusive and may share certain individual protection practices. The outcome of each choice is denoted by (s_1,c_1) for p_1 and (s_2,c_2) for p_2.

Because a degree of predictive uncertainty exists at the time the decision is made, however, these uncertainties are always treated explicitly in decision analysis. To describe the possible outcome of each set of practices, we determine a probability distribution function, P, that indicates which practices (s,c) may occur and the probability of their occurence.

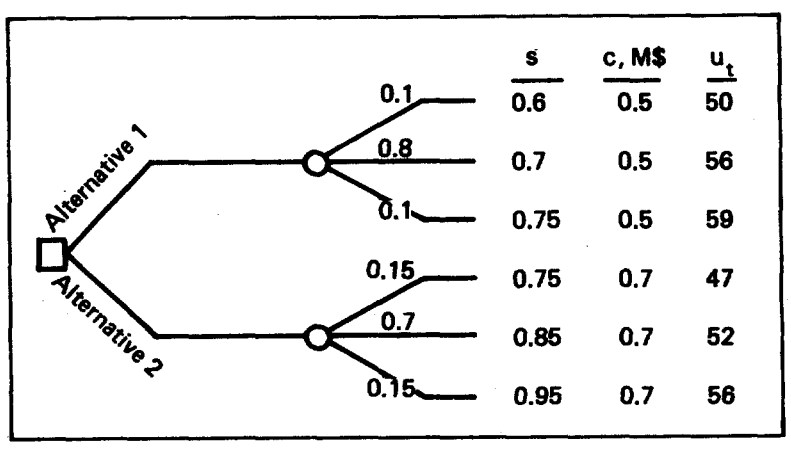

FIG. 20. Simple decision analysis model for selection of optimum hardening practices.

TABLE 1. Survivabilities and probabilities for two sets of protection practices.

Set of practices	Cost, $M	Survivability (s)	Probability (P)
p_1	0.5	0.60	0.10
		0.70	0.80
		0.75	0.10
p_2	0.7	0.75	0.15
		0.85	0.70
		0.95	0.15

Table 1 lists the outcomes and probabilities for the two sets of practices when the respective costs are fixed. According to these data, the set p_1 is less expensive and has less uncertainty associated with it; p_2 is more expensive and less certain, but it predicts a greater degree of survivability. Figure 20 shows a simple decision analysis model for determining u_t and lists u_t values calculated using Eq. (1). Table 2 lists a set of hypothetical utilities calculated using the values of s and c in Fig. 19.

The expected utility, $E(U_t)$, for each set of practices is calculated by summing the products of each utility and its associated probability for each outcome:

TABLE 2. Survivability and cost utilities for two sets of protection practices.

Parameter	Utility
Cost	
0.50	50
0.70	30
Survivability	
0.60	50
0.70	65
0.75	73
0.85	85
0.95	95

$$E(U_t) = \sum_{i=1}^{k} P_i U_{t_i} , \qquad (2)$$

where P_i are the associated probabilities. For practices p_1, $E(U_t) = 55.7$ and for practices p_2, $E(U_t) = 51.8$. On this basis, the expected utility of p_1 (with a lower survivability factor) is greater than that of p_2, and we would, therefore, select p_1. Although p_2 provides a higher survivability factor, its greater cost and high uncertainty make it the less desirable option.

SUMMARY

We have discussed an approach to the problem of designing effective protection practices of hardening communication facilities against nuclear EMP that do not interfere unduly with normal operations. Our goal is to develop a set of minimum requirements for hardening communication centers. Although we emphasize the use of EMP protection practices for the facility, we complement this approach by selecting equipment that meet minimum EMP-tolerance requirements.

Our approach consists of five steps:

- Determine and evaluate a minimum set of practices.
- Evaluate those practices recommended for EMP protection.
- Analyze costs of selected practices.
- Develop test requirements and test plans for a full-scale development facility.
- Incorporate the set of EMP practices into the EMC plan.

Although we have discussed the ingredients of each step of the approach technically, detailed procedures must be developed before these EMP practices can be applied to a specific facility problem.

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REFERENCES

1. *Engineering Design Handbook, Electromagnetic Compatability,* U.S. Army Materiel Development and Readiness Command, Alexandria, Va., DARCOM Pamphlet No. 706-410, March 1977.
2. E.F. Vance, J.E. Nanevicz, and G. August, "Technical Inputs and EMP Design Practices for Intrasite Cabling of Telecommunication Facilities," Stanford Research Institute, Menlo Park, Calif., Contract DAAG39-76-C-0021, July 1977.
3. E.F. Vance, "Design Guidelines for Treatment of Penetrations Entering Communication Facilities," Stanford Research Institute, Menlo Park, Calif., SRI Project 3149, Contract DCA100-74-C-0025, August 1977.
4. "Final Report/Inputs to Handbook of Engineering Design Practices," Boeing Aerospace Company, Seattle, Wash., D180-20396-1, December 1976.
5. "Intrasite Cabling Program, Problem Definition/Requirements Report," Boeing Aerospace Company, Seattle, Wash., December 1976.
6. "EMP Protection for AM Radio Broadcast Stations," Defense Civil Preparedness Agency, TR61-C, July 1976.
7. "EMP Protective Systems," Defense Civil Preparedness Agency, TR61-B, July 1976.
8. R.M. Bevensee, H.S. Cabayan, F.J. Deadrick, R.W. Egbert, L.C. Martin, E.K. Miller, J.T. Okada, A.J. Poggio, and J.L. Willows, "External Coupling of EMP to Generic System Structures," Lawrence Livermore Laboratory, Livermore, Calif., M-090 (1978).
9. R.V. Brown, A.S. Kahr, and C. Peterson, *Decision Analysis for the Manager* (Holt, Rinehart, and Winston, New York, 1974).
10. R.L. Keeney and K. Nair, "Decision Analysis for the Siting of Nuclear Plants—The Relevance of Multi-attribute Theory," *Proceedings of the IEEE* (Special Issue on Social Systems Engineering), March 1975, pp. 494-501.
11. *IEEE Transactions on Systems, Man, and Cybernetics,* (Special Issue on Behavorial Decision-Making), SMC-7, (1977).
12. R.L. Keeney and H. Raiffa, *Decisions with Multiple Objectives: Preferences and Value Tradeoffs* (John Wiley and Sons, New York, 1976).

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