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Electromagnetic Aspects of EMP Testing

October 1975

TM-75-14—Electromagnetic Aspects of EMP Testing—by Egon Marx

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

General considerations related to testing of complicated systems exposed to EMP by means of a simulator are presented, with special emphasis on the similarities and differences between the pulse generated by a high-altitude burst and the one generated by a simulator. Other aspects of a testing program are also discussed.

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1. INTERACTION OF THE SYSTEM AND THE EMP

1.1 Introduction

The detonation of a nuclear weapon above the atmosphere produces an electromagnetic pulse (EMP) that can affect electronic equipment over large areas on the ground.

One way to determine the vulnerability of a communications system to EMP is to subject the components and even whole nodes to a pulse produced by a simulator. The properties of pulses generated by different simulators and compromises that have to be accepted in a testing program are discussed in this report.

For a system to be tested for upset due to an EMP, it is important to have a good understanding of the interaction that has to be simulated. To a large extent, this undertaking has to be theoretical, due to the prohibition of high-altitude nuclear tests.

It is necessary to use an accurate description of the EMP produced by a high-altitude nuclear burst. The dimension of the region covered by the pulse due to a single burst can be as much as several thousand miles in diameter. The waveform, intensity, angle of incidence, and polarization of the wave vary greatly over such an area, and the relationships among them are not simple. Codes have been developed to compute the waveforms at different locations; their validity is limited by the number of approximations that have to be used to deal with the complicated processes brought about in the atmospheric burst.

The other consideration of importance is the interaction of the EMP with the system. The understanding of the coupling mechanism allows one to evaluate the importance of the differences between the test and an actual event.

1.2 Direct Energy Transfer at a Node

A node in a communications network acts as a receiving antenna to the EMP that sweeps over it. Although sometimes it is an actual antenna, most times it is a large conglomerate of conductors. Each element can be considered as an individual antenna, since local effects dominate at the initial portion of the EMP when the wave front first enters into contact with that particular element. At later times, the currents induced in the conductors flow from one to another, and the configuration of the whole node becomes important.

The propagation of electromagnetic effects is limited by the speed of light, according to the special theory of relativity. Since the wave front is traveling precisely at this speed, no induced currents or reflected waves can posibly get ahead of the original pulse.

Most of the studies of energy pickup by an antenna have been carried out for monochromatic or nearly monochromatic waves. For them, the coupling is most efficient when the size of the element is of the order of $\lambda/2$, where λ is the wavelength of the incident radiation. For a pulse, the square of the modulus of the Fourier transform of the time-amplitude gives the energy content in the pulse for a particular frequency range.

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The coupling of a receiving antenna with an EMP depends also on the direction of the incident pulse, that is, on the altitude of the nuclear burst, its distance from the node, and the orientation of this separation. For one configuration, the effect on a particular element is maximal, as can be determined in principle either theoretically or experimentally. In fact, such a determination for all the elements of interest appears very difficult for a complicated system, but some general guidelines might be forthcoming from such a study.

1.3 Currents Induced in Long Cables

A particularly efficient coupling mechanism for a communications node involves the long cables that frequently are connected to such a node. Large currents of the order of hundreds or even thousands of amperes can be induced in a cable, and they then go into (or come out of) the system. These effects are especially important for wide area illumination, in which the current rises quickly to a peak and then decays slowly as contributions from remote sections of the conductor arrive at the node.

It is relatively easy to determine the current induced in infinite conductors, but the effects of its termination at the node also have to be taken into account.

Some of these cables are buried, and others travel overhead, and the effects of the ground considerably influence the current induced in the conductor.

1.4 Effects of the Ground

An important factor always present in a problem involving EMP is the earth under (or over) the system being studied. In a calculation, the earth is normally represented by a semi-infinite medium with a plane boundary and given dielectric constant and conductivity. In most real circumstances, these are crude approximations. The earth is not flat, even locally, and its physical properties vary over sizable ranges both from one point to another and in time, due to its composition and water content, for instance.

The field above the earth consists of the incident wave and the reflected wave. Their relative phase, orientation, and magnitude can be determined for monochromatic waves through the well-known Fresnel formulas; the resultant pulse can then be obtained by integration over the frequency spectrum.

The transmitted wave also is determined by the Fresnel formulas, but another factor to be taken into account is the attenuation that the wave suffers propagating in this conducting medium. The distance δ in which a monochromatic wave of frequency $\omega/2\pi$ is reduced to 1/e, that is, 37 percent of its intial strength, is

$$\delta = (1/\sigma)\sqrt{\{(2\varepsilon/\mu)[1+\sqrt{(1+\sigma^2\varepsilon^{-2}\omega^{-2})}]\}}, \qquad (1)$$

where σ is the conductivity, ε the permittivity, and μ the permeability of the ground. Generally, μ is very close to μ_0, its value for the vacuum. In the low-frequency limit, $\omega<<\sigma/\varepsilon$, equation (1) reduces to

$$\sigma \approx \sqrt{(2/\mu\sigma\omega)}. \qquad (2)$$

That is, the penetration depth decreases with increasing frequency. In the high-frequency limit, $\omega>>\sigma/\varepsilon$, equation (1) becomes

$$\sigma \approx (2/\sigma)\sqrt{(\varepsilon/\mu)}, \qquad (3)$$

an expression that has no explicit frequency dependence.

If one uses as typical values for the ground a conductivity of 5×10^{-3} ohm^{-1} m^{-1} and a dielectric constant of 17, the transition region between these two limits centers on a frequency of 5 MHz, which corresponds to $\omega = \sigma/\varepsilon$ This frequency is well within the spectrum of the EMP.

The overall frequency dependence of the reflection and transmission or refraction coefficients is quite complicated, and their implications for pulses depend strongly on the spectrum of the incident field.

1.5 Effects of Structures

The field reaching the components of a communications system is further affected by the structures in which they are housed. One extreme is equipment in an especially shielded room, where essentially no external radiation can penetrate. The extent to which an incident wave is attenuated by the metal that is part of the building can vary between wide limits and has to be taken into account. The field is modified further when it is scattered by the conducting material that forms part of the equipment and that can be considered as part of the receiving antenna that absorbs the incident radiation.

The fields that affect directly the conductors that carry the signals in the system are very different from the field that would exist in the absence of these structures.

1.6 Response of a Node

The EMP on a node causes currents in the conductors that normally carry the communications signals and potential differences between different parts of the node. These currents can disrupt the system in two ways. By "upset," the operation of the equipment or the nature of the signal being transmitted changes temporarily, so that a message does not reach its destination in the original form. The other disruption, "damage" to the equipment, is reflected by physical changes in the components that require replacement or repair.

Many complicated systems can be conceptually separated into two parts, the ground and signal networks. This simplification reduces the scope of calculations that have to be performed to predict the response of a given node.

1.6.1 The Ground Network

The ground network is formed by the shielding of cables and conductors, the cabinets, bars, and other supporting structures for the equipment, which are connected to each other and usually to earth ground. The currents induced in these elements are large, up to thousands of amperes. Long cables and large ground loops are particularly effective in their coupling to the EMP.

1.6.2 The Signal Network

The signal network consists of the conductors and devices that carry and process the signals that travel through the communications system. The current induced in these elements is much smaller, since they are usually shielded by the ground network. They can be associated with transfer functions between the shielding of cables and the interior conductors, and similar descriptions suffice for the more or less local effects for other elements. The different transfer mechanisms can be considered for many configurations as a problem independent of interactions with other parts of the node. The reradiation effects of these small currents can be neglected. It is important to detect any unshielded portion of this network, since large currents can be introduced through them into other components.

1.7 Critical Components of a Node

The currents and voltages induced in the signal network affect different components in different ways. Some components are upset or damaged more easily than others, and they respond to a particular feature of the pulse more strongly. It is, then, of primary importance to determine the currents or voltages induced at the particular locations of these most sensitive components. On the other hand, redundancy built into a specific node might make damage to a given component relatively unimportant, whereas other components are essential to the functioning of the system. Those other components that are most sensitive to the EMP are the critical components that have to be hardened and protected with special care, as well as monitored during any testing program.

2. LARGE-SCALE SIMULATORS

2.1 Purpose

In view of the restrictions on realistic testing of a communications system in an EMP environment, the response of the different nodes has to be either calculated or measured by use of the field produced by a simulator. The extent to which the EMP is faithfully reproduced depends on the purpose of a particular test. A simulator that tests the whole node or a large subsystem presents different design problems from a field generator used in testing components or small subsystems.

2.2 Design Considerations

The general characteristics of the fields, as well as the relative magnitude and orientation of the electric and magnetic vectors, differ from the induction zone to the radiation zone.

For determination of the response of a node to a wave, that is, a pulse of electromagnetic radiation, an antenna should be used at a relatively large distance from the node, so that the system can be affected mainly by the radiation fields.

It is necessary to determine also what characteristics of the EMP have to be reproduced so that the upset or damage is comparable to that in a real-threat situation, characteristics such as the peak amplitude, rise time, and total energy.

The distinguishing aspects of a pulse are its shape, its amplitude, its polarization, its direction of propagation, and the area that it covers.

Two aspects in the shape of the pulse have to be considered: the time dependence at a fixed location and the spatial configuration. The time dependence has frequently been idealized, in the EMP dialogue, to the double exponential

$$f(t) = a[\exp(-\alpha t) - \exp(-\beta t)], \tag{4}$$

where $1/\beta$ is the short rise time and $1/\alpha$ is the much longer decay time; the field of the simulator is then compared to this waveform. The spatial dependence of the plane wave is a result of the approximation of a spherical wave front to a plane wave when the region of interest is small compared to the radius, and the direction of propagation is only a matter of the relative location of the source and the system. The EMP is expected to be linearly polarized, which is relatively simple to achieve for the fields of an antenna.

The properties of a threat-level EMP impose contradictory demands on the simulator. For instance, a source far from the installation is required to reproduce a plane wave, but this requirement severely restricts the level of intensity that can be obtained at the site. This restriction might be unimportant when linear effects are studied in low-level tests, but most systems contain nonlinear elements, and damage is intrinsically nonlinear. A short rise time can be readily obtained from a small antenna, but this problem is major for a large simulator required to produce threat-level fields. Consequently, the specific objectives of the test and the nature of the node will have to determine the emphasis to be placed on the achievement of the different desiderata.

2.3 Properties of the Electromagnetic Fields

All electromagnetic fields are solutions of Maxwell's equations and are determined by the sources and the boundary conditions. These facts are true for both the EMP produced by a nuclear burst and the fields of all simulators. In some simple cases, it is possible to calculate these fields accurately, but in general, they have to be measured or estimated from models.

2.3.1 Free-Space Fields

When the currents and charges that give rise to a field are known, and the presence of conducting and dielectric bodies in their vicinity can be neglected, it is possible to find the fields in terms of integrals over the sources.

Maxwell's equations in free space, written in rationalized MKSA units, are

$$\nabla\cdot\vec{E} = \rho/\varepsilon_0, \tag{5}$$

$$\nabla\times\vec{E} = -\partial\vec{B}/\partial t, \tag{6}$$

$$\nabla\cdot\vec{B} = 0, \tag{7}$$

$$\nabla\times\vec{B} = \mu_0\vec{J}+\varepsilon_0\mu_0\partial^{\rightarrow} \tag{8}$$

Equations (6) and (7) imply that these fields can be obtained from a vector potential and a scalar potential by means of the equations

$$\vec{B} = \nabla\times\vec{A}, \tag{9}$$

$$\vec{E} = -\partial\vec{A}/\partial t-\nabla\Phi; \tag{10}$$

These potentials then satisfy d'Alembert's equations

$$(1/c^2)\partial^2\vec{A}/\partial t^2 - \nabla^2\vec{A} = \mu_0\vec{J}, \tag{11}$$

$$(1/c^2)\partial^2\Phi/\partial t^2 - \nabla^2\Phi = \rho/\varepsilon_0 \tag{12}$$

in a Lorentz gauge, where the potentials satisfy

$$\nabla\cdot\vec{A}+(1/c^2)\partial\Phi/\partial t = 0 \tag{13}$$

and $c = \sqrt{(\varepsilon_0\mu_0)}$ is the speed of light in vacuum. Integration of these equations by use of retarded Green functions yields

$$\Phi(\vec{x},t) = \frac{1}{4\pi\varepsilon_0}\int\frac{\rho(\vec{x}',t-|\vec{x}-\vec{x}'|/c)}{|\vec{x}-\vec{x}'|}\ d^3x' \tag{14}$$

$$\vec{A}(\vec{x},t) = \frac{\mu_0}{4\pi}\int\frac{\vec{J}(\vec{x}',t-|\vec{x}-\vec{x}'|/c)}{|\vec{x}-\vec{x}'|}\ d^3x', \tag{15}$$

which can be written as

$$\Phi = \frac{1}{4\pi\varepsilon_0}\int\frac{[\rho]d^3x'}{R}, \tag{14'}$$

$$\vec{A} = \frac{\mu_0}{4\pi}\int\frac{[\vec{J}]d^3x'}{R}, \tag{15'}$$

where

$$R = |\vec{R}|, \quad \vec{R} = \vec{x} - \vec{x}' \ , \tag{16}$$

and the brackets indicate that the sources are taken at the retarded time t - R/c.

The fields, derived from the above potentials through equations (9) and (10), are

$$\vec{B} = \frac{\mu_0}{4\pi c}\int \left[\frac{\partial \vec{j}}{\partial t}\right] \times \frac{\vec{R}}{R^2}\, d^3x' + \frac{\mu_0}{4\pi}\int [\vec{j}\,] \times \frac{\vec{R}}{R^3}\, d^3x', \tag{17}$$

$$\vec{E} = -\frac{\mu_0}{4\pi}\int \left[\frac{\partial \vec{j}}{\partial t}\right] \frac{1}{R}\, d^3x' + \frac{1}{4\pi\varepsilon_0}\int \left\{ \left[\frac{\partial \rho}{\partial t}\right] \frac{\vec{R}}{cR^2} + [\rho]\frac{\vec{R}}{R^3} \right\} d^3x'. \tag{18}$$

The vector $\vec{x}'$ ranges over the region of the sources and can be limited by a magnitude ρ_0, the size of the source. For a field point $\vec{x}$ such that $r \gg \rho_0$, the terms containing $[\partial\vec{j}/\partial t]$ or $[\partial\rho/\partial t]$ decrease like 1/r with the distance from the source, whereas those derived from $[\vec{j}\,]$ or $[\rho]$ decrease like $1/r^2$. The first ones then dominate at large distances, give a finite contribution independent of r when the Poynting vector $\vec{E}\times\vec{H}$ is integrated over a sphere, and are called "radiation" fields. The other terms are labelled "induction" fields.

The Poynting vector represents the power flow radiated by the sources. In the radiation zone, the fields $\vec{E}$ and $c\vec{B}$ are perpendicular to each other and have the same magnitude, and the Poynting vector is radial.

For some idea of the location r_0 of the ill-defined boundary between the radiation and induction zones, the magnitudes of the integrands are set equal, whence

$$|\partial\vec{j}/\partial t|/cr_0 \simeq |\vec{j}\,|/r_0^2 \ , \tag{19}$$

which gives

$$r_0 \approx c|\vec{J}||\partial\vec{J}/\partial t|^{-1} . \tag{20}$$

The quantity

$$\tau^{-1} = |\vec{J}|^{-1}|\partial\vec{J}/\partial t| \tag{21}$$

represents the rate of change of the sources and is independent of the amplitudes, and τ is of the order of magnitude of the rise time or decay time of the pulse. If the simulator has a rise time of 3 nsec, $r_0 \simeq 1$ m, whereas for a decay time of 1 μsec, it increases to $r_0 \simeq$ 300 m.

Further simplifications are possible when the wave is nearly monochromatic (the EMP is not). When it is, one can distinguish three zones for a distance r from the source, such that

$\rho_0 << r << \lambda$ near (static) zone,

$\rho_0 << r \sim \lambda$ intermediate (induction) zone,

$\rho_0 << \lambda << r$ far (radiation) zone,

where the size of the source ρ_0 was assumed to be much smaller than the wavelength λ. For a pulse with a broad bandwidth, only the radiation zone is clearly defined.

The fields in the induction zone do not resemble those of a plane wave, and the flow of energy includes not only that to be dissipated as radiation, but also a significant amount that is basically going back and forth near the sources. This field can be important if the receiving "antenna" is close to the emitter. Also, calculations under the assumptions that fields $\vec{E}$ and $c\vec{B}$ are perpendicular to each other and of equal magnitude have to be reexamined for locations in the induction zone.

2.3.2 Local Modifications

The fields obtained above can serve as an approximation or as a starting point for further calculations. In a realistic situation, there are significant effects of the ground and of structures, if any. The ground effects suffer from uncertainties due to varying soil and weather conditions and thus can be only estimated. They are of importance in calculations related to measurements of the field of an antenna and to the currents induced in long cables by the simulator. The effects of a structure with complicated configurations of conductors are much more complicated, and the multiple reflections can change the nature of the field in a radical manner. For the field inside a building, the magnitude due to an incident pulse depends on the amount of shielding provided by the construction materials and internal structures. The magnitude can vary greatly and have comparable effects for the EMP and for the pulse of a simulator.

2.4 Emitting Antennas

It is possible to use a large variety of antennas to generate a pulse of radiation, and each configuration has advantages and drawbacks. These can be studied theoretically for simple configurations, which can later be modified, and the changed fields can be determined experimentally. The radiator can vary from a simple dipole, represented by a thin wire, to bicones, cylinders, toroids, and their combinations. The generators can provide either a single pulse or a continuous wave type of operation. The size of the antenna is related to the level of the fields that it produces and the area of illumination, and the design is limited by conflicting theoretical and practical considerations.

2.4.1 TEMPS

An example of a pulse generator is the transportable EMP simulator (TEMPS). The pulse is produced by a spark in a Marx generator and radiated by a two-part antenna. It has a high-frequency launcher in the form of a biconic antenna, which is responsible for the early part of the pulse with a rise time from 3 to 10 nsec, and a low-frequency radiator consisting of a tapered dipole formed by a number of long wires and terminated through resistive loading to earth ground. The total length is approximately 300 m, and this cylinder is effective later in the pulse, which has a decay time of about 800 nsec. The initial peak is relatively well defined, but the later period is characterized by a considerable amount of oscillations; the overall shape, then, has to be compared to the double exponential assumed for the EMP.

The amplitude of the field can be varied within certain limits by regulation of the voltage and the pressure in the spark gap, but low-level fields have to be obtained by location of the TEMPS far from the test area. The maximum field reaches threat level in an area on the plane of symmetry of the TEMPS about 50 m from the bicone, a location where the field is highly inhomogeneous and which is well within the induction zone for the decaying part of the pulse.

The free-space fields can be calculated either from the currents or from the measured fields above the ground. The peak values of the amplitudes show that the fields originate near the center of the bicone for the early times, and the magnitude decays roughly as the inverse of the distance to this point, as expected for radiation fields.

2.4.2 Continuous-Wave Radiators

Another possibility for an emitting antenna is a source that produces a pulse that is repeated at a high rate and that emits an almost monochromatic wave. The response of the system for high frequencies can be measured easier and results are more precise. On the other hand, the frequency content of the pulse can range over a wider spectrum than is readily attainable with a CW source, and the strength of the wave emitted at a single discharge is generally higher. Furthermore, so that how a node responds to a pulse from CW measurements can be inferred, computation is necessary by use of the Fourier transform of the signal, which not only demands a knowledge of the response to a sufficiently large part of the spectrum, but also assumes that the system is linear in its interaction with the EMP.

2.5 Current Injectors

The field of a pulse generator such as the TEMPS effectively covers a relatively small area, which is not adequate to simulate the effects of currents induced by the EMP on long cables, known to be an important coupling mechanism between the pulse and the node. Thus, the pulse generated by the simulator has to be combined with the pulse from a device that injects currents on the shielding of long cables, which in turn will transfer in the appropriate manner to the internal conductors. Some current injectors are basically charged capacitors coupled to the shielding of the cable so that a current pulse of the right magnitude and shape is produced when they are discharged. Other designs with inductive couplings are possible, also.

The current pulse induced in a long cable can be determined to a reasonable approximation from analytical models, scale modelling, and past experience. The pulse is different for overhead and for buried cables, especially in rise time; it is much larger in buried cables. Current injectors can reproduce either shape, regardless of the actual type of cable they are attached to.

A problem that arises is the synchronization of the simulator with the current injectors on different cables. It does not appear to be feasible to preset the firing time of the TEMPS, for instance, within a few nanoseconds, which would be required to coordinate the peaks of the corresponding pulses. The pulse of the simulator itself probably has to be used to fire the current injectors, and it is questionable to what extent this procedure reproduces the effects of the peak of the fields. If the rise time of the injected current pulse were much longer than several nanoseconds, it would not contribute significantly to the evaluation of the effects of the initial peak, but only of those of the ringdown of the system at later times.

2.6 Voltage Pulsers

Voltage pulsers use some type of waveguide, such as parallel plates or wires, in the immediate vicinity of the equipment to be tested, coupled to a voltage generator. It is a matter of interest to determine to what extent the fields of a wave propagating in free space are reproduced by those of a wave propagating in a particular type of waveguide, especially in the presence of other conductors inside the waveguide. They could be used also with an emitting antenna to produce a particular local effect.

3. COMPLEMENTARY TESTING

3.1 Bench Tests

The node as a whole should be subjected to pulses so that, as far as possible, upset and damage are limited to a minimum. The readings of currents, voltages, and fields then have to be correlated to the possiblity of damage to the critical components.

One way to test a component is to remove it (or another with the same characteristics) from the node and subject it to bench tests. In this way, it can be subjected to pulses of current, voltage, or electromagnetic energy, and the failure rate under given conditions can be determined. The values of the parameters that cause damage then are compared to those expected in the different locations in the system where this component is found.

One major difficulty is the determination of the relevant characteristics of the pulse that cause the upset or damage. It could be the rise time, the frequency of oscillation, the amplitude, the power, the total energy, and so on. If this aspect of the testing is neglected, results obtained from the wrong kind of pulse or CW can be irrelevant to the actual EMP threat.

Another important observation on such a testing program should determine the uniformity among different units of the same type of component.

Some type of bench testing can be extended to also include small subsystems of a node.

3.2 Scale Modelling

It is possible to set up a model of a system to be tested in a laboratory, so it can be subjected to the effects of pulses from a correspondingly reduced antenna.

The wave equation in a conducting medium is

$$\nabla^2\vec{E} - \varepsilon\mu\partial^2\vec{E}/\partial t^2 - \mu\sigma\partial\vec{E}/\partial t = 0 \ , \tag{22}$$

which is invariant under a transformation

$$\vec{x} \rightarrow \lambda\vec{x} \ , \ t \rightarrow \lambda t \ , \ \sigma \rightarrow \sigma/\lambda \ . \tag{23}$$

That is, if the model is of a size 1:100 of the original, the rise time of the pulser has to be 1/100 of the one to be used on the site, and the conductivity (of the ground, for instance) has to be increased by a factor of 100. The permittivity ε and the permeability μ were assumed to remain constant, and in practice, they are more difficult to change than the conductivity. In a real situation, μ is nearly equal to the constant μ_0, but ε varies significantly with the composition of the surface (for instance, the water content of the ground) and with frequency. Strictly speaking, Maxwell's equations in the form of equations (5) to (8) are no longer valid when ε depends on frequency.

Such scale modelling could be useful for experiments in which the location of the pulser is changed for finding maximum coupling and the currents induced in long cables and for similar testing that is difficult on the original site. The question of the detail of the model limits the validity of the answers that are obtained in this manner.

3.3 Subsystem Testing

Experiments can be designed to test a subsystem of the node that is particularly sensitive or a replica of such a subsystem--for example, another computer.

This approach can be useful also for validation of analytical estimates of upset and damage, which become progressively less practical as the size and complexity of the object of the test increase.

Results for different subsystems can then be combined so that how the EMP affects the node can be predicted as a whole.

On a different scale, a similar synthesis has to be carried out, so that how a HEMP affects a communications network can be evaluated after the responses of the nodes have been determined.

4. RESPONSE OF A NODE TO A SIMULATOR

4.1 Introduction

It is quite obvious from the foregoing discussion that the simulator produces a pulse that differs significantly from the actual HEMP. The consideration of these differences is important for a valid assessment of the hardness of the node.

One approach is the simulation of the worst possible case of EMP, increased by an additional safety factor against errors and miscalculations. Such a requirement would be in all likelihood uneconomical in both the testing and the demands on the hardness of the system. Thus, a more modest view of a test program should suffice to ascertain the hardness of the system with a sufficiently large probability.

Within this framework, an understanding of the interaction between the node and the simulator allows the most efficient test program to be followed. Scale modelling can be of great help in the determination of optimal coupling between the system and the pulse. Also, the design of the simulator is determined to some extent by the relative importance of the parameters of the pulse that it produces, with respect to the coupling to the node.

4.2 Location and Orientation of the Simulator

In each test, a choice has to be made as to where the simulator will be located with respect to the site, how it will be oriented, and, to some extent, what shape it will have if the simulator can be deformed. The current or voltage induced at a particular component depends on these variables and is maximal for values that can be determined. In general, though, this configuration differs for each component and many times depends further on the internal connections of a node, such as a switch, at the time of the test. Some configurations induce a larger response throughout most of the components, and others most strongly affect some critical subsystem; among all these configurations, a reasonable number has to be selected for a valid assessment of the hardness of the system. They should be determined beforehand from theoretical analysis, scale modelling, and past experience; if this timing is not possible, they should be evaluated by a change in the configuration of the simulator, until a pattern emerges.

The simultaneous use of current injectors gives more flexibility to the testing, and their input can be calibrated to give a reliable upper bound.

4.3 Level of the Test

It is desirable that, at least in some of the testing, the intensity of the pulse be of the order of magnitude of that from a real threat situation, so that the ever-present nonlinear effects can be observed. Once the characteristics of a certain type of equipment are understood, other similar units can be tested at low level, to determine the coupling to the EMP.

There is a lower limit to the intensity of the pulse produced by a simulator such as the TEMPS. Positioning the simulator farther away decreases the level at the test site, but such action may be restricted by terrain. Under difficulty, a different and simpler simulator can be used for low-level tests, which can also be used to collect data that are easily gathered with a small device, but become too costly with one like the TEMPS. This procedure could include effects of the direction of propagation and polarization of the pulse.

4.4 Connectivity Effects

In a node such as a switch, the particular interconnection in the signal network is always one of a large number of possible ones. The very one is determined partly by the number and type of calls being processed and partly at random. It is not practical to test all possible configurations of the switch, and they have to be grouped into states that show small dispersion of the measurements within a group. If the system is sufficiently complicated, a statistical approach to the failure of a type of component is suggested.

4.5 Degradation Effects

At low-level testing, the facility is not changed by such tests, and successive pulses find the same physical system. On the other hand, in threat-level testing or in a multiburst EMP environment, damage to a number of noncritical components can change significantly the coupling characteristics of the node. A careful determination of the most sensitive components can indicate the possible changes in the node, but in general, such a prediction would depend on too many circumstances to be reliable.

It is not clear to what extent it is desirable to perform such a partially destructive test. Possibly, tests on replicas of subsystems could indicate the importance of the changes introduced in the system by the failure of some of the components.

4.6 Synchronization of Simulators

When a pulse sweeps over a facility, it reaches different parts of the building in a well-defined sequence of time intervals, which depends on the direction of propagation of the pulse. It also determines the characteristics of currents induced in long cables as functions of angles of incidence.

A decision has to be made about the degree of accuracy with which the current injectors, for instance, are going to reproduce the difference between the effects of the simulated pulse and the EMP. If the current injectors are triggered by the pulse from the main simulator, their main contribution to the testing is limited to power effects of the late-time part of the pulse and the ringdown of the system.

4.7 Resonant Modes

Experience with simulators and EMP testing indicate that the general characteristics of a time-amplitude trace are an initial peak and a subsequent oscillatory part with a slowly decreasing amplitude. Which part of the pulse affects a particular component depends on the nature of the upset- or damage-causing characteristic.

4.7.1 Direct Effects of the Incident Wave

The incident wave results in a peak in the current or voltage curve that roughly corresponds to the peak of the incident field. For a simulator, the wave is generally characterized by a short rise time of a few nanoseconds, a fairly high amplitude (possibly up to a maximum for threat-level tests), and a similar decay time. Components that are affected by such a type of signal, even for a fairly low level, might be upset. For instance, digital information transmitted by essentially square pulses can be contaminated by such a peak.

This wave might be contrasted to the double exponential waveform assumed for the EMP. The EMP waveform has a similar rise time, but then decays slowly from the maximum without oscillations. It is not clear to what extent this double exponential waveform represents an overidealization of the actual waveform.

4.7.2 Late-Time Oscillations

The response of the node to the incident pulse initially follows the time pattern of the pulse, but for later times, oscillations build up that can exceed in amplitude that of the initial peak. That oscillations build up represents a resonance phenomenon in which the behavior of the perturbation induced in the node is no longer determined by the incident pulse, but obeys the constraints imposed solely by the internal structure of the node. The energy absorbed from the pulse might in this manner be concentrated on certain components and damage them quite independently from the direct pulse effects.

5. MEASUREMENTS

5.1 Design of Probes

Some of the quantities to be measured at appropriate locations in the facility are currents, voltages, and components of the electric and magnetic fields. The signals are picked up by probes and transmitted through dielectric waveguides to oscilloscopes, which display the time-amplitude traces.

Many considerations should go into the design of these probes for a reliable measurement. The probe itself should not distort appreciably the quantity to be measured. This effect might be important for the measurement of the electric field "at a point" by the placement of a sizable metallic box. The signal transmitted from the probe also can differ significantly from the quantity that is being measured by intrinsic characteristics of the probe, such as limitations at the high-frequency end of the spectrum.

Physical size of the probes, too, can limit the choice of location for these probes.

5.2 Location of Probes

The decision on where to place a probe acquires a special importance when the number is small and limits the collection of the data. The time between firings of the simulator and that needed for relocation of the probes can easily be 10 min.

It is desirable to place a probe as close as possible to a critical component of the system. If it is not possible to do so due to the physical configuration of the facility or to the size of the probe, how the pulse affects the component might have to be extrapolated by analysis.

Other general guidelines obtained from past experience in EMP testing suggest that those components closest to the entrance paths of long cables are more exposed to failure than those removed from these entry points. However, this statement is not necessarily true for a complicated system where other points of concentration of energy might occur. In general, high currents on the shielding of a cable indicate a correspondingly large (on a different scale) current transferred to interior conductors.

5.3 Qualitative Observations

In any record of a test, the testing personnel need a means to record observations that cannot be quantified or even predicted in advance. These might be visual observations on the equipment or damaged components or circumstances that could have affected the outcome of certain tests.

In general, a description of the damage to a component, beyond the specification of its identity, would require such an entry.

5.4 Functional Evaluation

Facility degradation due to upset of components or subsystems generally is not described by the results of measurement with probes or by qualitative observation, although such observations might be useful to record gross malfunctions of the equipment. Detection of a small-scale upset of the facility might be difficult, and detailed checking must be programmed so that no fault is overlooked. When a computer is part of the system, a program that finds any changes in the stored information is a valuable part of the test measurement.

Also, it is desirable to test all the different modes of operation of a facility, so that damage or upset in a seldom-used, but potentially important, function is not overlooked.

6. ANALYTIC MODELLING

6.1 Introduction

The theory of the propagation of electromagnetic waves and their interaction with matter on a macroscopic scale is well established and expressed in a set of partial differential equations, Maxwell's equations, which apply widely. Difficulties arise when system response to EMP is evaluated. These difficulties are thus not basic in nature, but brought about by the complexity of the system and whether a node can be successfully modelled in this manner thus depends on its size and complexity.

On the other hand, the generation of the EMP and the damage of components are much more complicated in principle. An analytic model cannot be relied on for correct results, even if carried out with great precision.

6.2 Representation of the Pulse

There are relatively little experimental data on the EMP generated by an exoatmospheric nuclear burst, and most models of the pulse have been generated analytically.

The order of magnitude of the amplitudes at different locations can be calculated, but the shape of the pulse probably depends more critically on the detail of complex processes in the interaction of electrons and ions with the primary products of the burst. In such a situation, it is just as useful to use a convenient analytical expression for the wave shape, such as the double exponential, as a more complicated shape that is not likely to be closer to the actual EMP. In other calculations, it might be more convenient to use a slightly different analytical formula that gives a curve of roughly the same characteristics.

The pulse produced by a simulator is much better known and could in principle be calculated from the known configuration of the pulse generator and the emitting antenna. Uncertainties associated with a gaseous discharge and complications due to the actual structure of the simulator do not make this a very attractive alternative to the measurement of the pulse shape. On the other hand, such calculations are important in the design of new and better types of simulators.

6.3 Representation of Components

Single components such as transistors can be reasonably well represented by circuits with a small number of parameters. These circuits can then be used to model the functioning of much more complicated devices, but a limit is soon reached when the number of components goes into the thousands.

These equivalent circuits also are designed to represent the normal behavior of a component and might give a completely useless extrapolation under conditions leading to damage. Another limitation of such an approach is the failure to take into account the absorption and emission of radiation, which is important for pulses or sufficiently high-frequency signals.

6.4 Calculations for Long Cables

It is relatively simple to model long cables by infinite cylinders, and also a large body of experience with linear antennas is useful for short segments of a line.

As is generally true in calculations of this nature, the presence of the ground complicates significantly the boundary conditions in the problem.

Approximate results should be applied carefully in extreme cases. For instance, the current induced in an infinitely long, perfectly conducting cylinder by a pulse in the shape of a double exponential was found[1] to decay like 1/(log t) for late times. This very slow rate of decay is unphysical and is due to the neglect of the resistivity of the cylinder. If it is taken into account,[2] the induced current decays exponentially for late times proportional to amplitude of the pulse. Another example is furnished by the current induced in such a cylinder by a wave when the direction of propagation is almost parallel to the axis; then the current tends to infinity when the angle tends to zero for a perfect conductor, but the current tends to zero when the resistivity is properly taken into account.

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[1] *P. R. Barnes, EMP Interaction Notes, Note 64, Air Force Weapons Laboratory, Kirtland AFB, NM (March 1971).*

[2] *E. Marx, Harry Diamond Laboratories, TR-1617 (January 1973).*

The importance of the energy that is coupled into the system through long cables increases as the shielding of the node itself is improved. Accurate calculations of the currents induced on the shielding of the cable and those transferred to the internal conductor are of great help.

6.5 Response of Small Subsystems

Analytic modelling of parts of a system should be developed so that a test can be evaluated on components that are not directly accessible to the probes, and critical parts of a node can be studied when the inputs can be determined.

If the node is small and simple, an analytical model might suffice for evaluation of its response to EMP, especially if it is well shielded against the direct effect of radiation. If so, reliable methods are needed so that the energy picked up by cables can be calculated.

6.6 Singularities Expansion Method

For several different configurations of antennas, the response at late times is a combination of damped exponentials.[3] This general behavior has been interpreted as a manifestation of the dominance in the Fourier transform of poles that are close to the real axis, whence the transfer function is approximated by an expansion of the form

$$F(\omega) \simeq \Sigma_i \alpha_i/(\omega-\omega_i) \quad , \qquad (24)$$

where the ω_i are the locations of complex poles. Such an approximation dominates the behavior of the time amplitude after the incident pulse has passed over the antenna.

These concepts can be extended to more complex systems, especially because the expansion in the singular terms has given good results for antennas of quite different shape. Furthermore, measurements of EMP effects on fairly complicated systems show the presence of damped sinusoids for late times.

Thus, it would be possible to describe the late-time ringdown of a node by such an expansion, and the locations and strengths of the poles could be determined by analysis or, more plausibly, from measurements. This transfer function is independent of the pulse used to excite the system.

6.7 Modelling of a Node

For a relatively simple node, analytical methods discussed above can give a fairly accurate prediction of its response to EMP. On the other hand, as a node grows more complicated, more general principles are needed to avoid detailed calculations, which become impractical and unreliable. As in other problems, a large degree of complexity

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[3] *C. E. Baum, EMP Interaction Notes, Note 88, Air Force Weapons Laboratory, Kirtland AFB, NM (December 1971).*

eventually means a simplification, where the statistical laws become more important than meaningless microscopic predictions. It is then necessary to find the relevant parameters that describe the system and determine the reliability of predictions obtained in this manner.

6.8 Complex Systems

The EMP covers areas of millions of square miles, and no simulator can reproduce the simultaneous effects on many different nodes. It is possible to use several simulators, but the synchronization would present great difficulty. Because the links between nodes in a communications system are not particularly sensitive to EMP, it is reasonable for researchers to rely on the experimental data on the nodes and calculate through an analytical model the overall reliability of the communications network.

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