Sensor and Simulation Notes

Note 240*

January 1978

CLEARED
FOR PUBLIC RELEASE
PL/PA 5/15/97

EMP Simulators for Various Types of Nuclear EMP Environments: An Interim Categorization

Carl E. Baum
Air Force Weapons Laboratory
Kirtland AFB, NM 87117

Abstract

Nuclear EMP environments have various forms depending on the location of the nuclear detonation and the location of the system exposed to the EMP environment. One can simulate these environments with various degrees of completeness on such systems. A simulator produces an EMP environment on a system of interest in a manner which can be related to the type of nuclear weapon detonation being simulated. There are many types of EMP simulators, some of which have been realized in one or more existing EMP simulators. Some types of EMP simulators only exist conceptually at the present time. This note discusses the basic types or categories of EMP simulators. Such categories are based on the electromagnetic geometry of the simulator structure and electrical sources, including the location of the system under test and other nearby materials significantly influencing the electromagnetic fields. The various types of simulators are suitable for simulating different types of nuclear EMP environments. A particular type of EMP environment can be simulated with different degrees of completeness depending on the type of simulator used. In this note we only consider nonnuclear types of energy sources and in some cases high energy photon and electron sources. The EMP simulators considered range from ones which illuminate entire systems, down to ones which drive individual penetrations into systems. Not considered here are techniques for testing individual components or "black boxes" or driving the system at some intermediate point along an internal coupling path.

---

*This paper is an adaptation of Sensor and Simulation Note 151, 13 July 1972.

PL 96-1122

IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. AP-26, NO. 1, JANUARY 1978

WL-EMP-SSN-240

Sensor and Simulation Notes
Note 240

nuclear effects, source region radiation, electromagnetic pulse simulation

EMP Simulators for Various Types of Nuclear EMP Environments: An Interim Categorization

CARL E. BAUM, MEMBER, IEEE

Abstract—Nuclear EMP environments have various forms depending on the location of the nuclear detonation and the location of the system exposed to the EMP environment. One can simulate these environments with various degrees of completeness on such systems. A simulator produces an EMP environment on a system of interest in a manner which can be related to the type of nuclear weapon detonation being simulated. There are many types of EMP simulators, some of which have been realized in one or more existing EMP simulators. Some types of EMP simulators only exist conceptually at the present time. This note discusses the basic types or categories of EMP simulators. Such categories are based on the electromagnetic geometry of the simulator structure and electrical sources, including the location of the system under test and other nearby materials significantly influencing the electromagnetic fields. The various types of simulators are suitable for simulating different types of nuclear EMP environments. A particular type of EMP environment can be simulated with different degrees of completeness depending on the type of simulator used. In this note we only consider nonnuclear types of ernegy sources, and in some cases high energy photon and electron sources. The EMP simulators considered range from ones which illuminate entire systems, down to ones which drive individual penetrations into systems. Not considered here are techniques for testing individual components or "black boxes" or driving the system at some intermediate point along an internal coupling path.

FOREWORD

For a little over a decade now this author has been developing EMP simulator concepts and performing the electromagnetic design for numerous specific EMP simulators for the U.S. Air Force and other agencies. Over the years patterns started to emerge among the various types of EMP simulators. These patterns suggested where certain simulator types might be absent, and so in completing the patterns new EMP simulator types were developed. As time goes on, new types are developed and old ones are split into various categories as well. This note summarizes the present state of the art in EMP simulator design including only the electromagnetic aspects. Hopefully this note will help clarify the reader's thinking in regard to the various types of EMP simulators, the relationships among the various types of EMP simulators, what type of EMP environment a particular type of simulator can be used for, and some of the general advantages and limitations as far as producing quality EMP environments associated with each type of EMP simulator.

This note will not go into the mathematical details of the boundary value problems associated with each simulator type. These are treated by this and other authors in the extensive references which provide a bibliography of the subject. This paper attempts to summarize the general geometries, major performance features, and relative advantages of the various simulator types in the context of the particular type of EMP each is intended to simulate.

***

> *Socrates:* Then the argument would lead us to infer that names ought to be given according to a natural process, and with a proper instrument, and not at our pleasure; in this and no other way shall we name with success.
>
> from the dialogue *Cratylus* by Plato,
> translation by Benjamin Jowett

Manuscript received July 26, 1976; revised May 20, 1977. This paper is an adaptation of Sensor and Simulation Note 151, dated July [illegible]8, 1972, for this special issue [91].

The author is with the Air Force Weapons Laboratory, Kirtland Air Force Base, Albuquerque, NM 87117.

I. INTRODUCTION

Since EMP simulators are a major part of EMP technology, it is appropriate to review this subject for this special issue. EMP simulators cannot be properly understood in isolation. At a minimum one needs some appreciation of the EMP environment, and for this the reader is referred to Longmire's paper in this issue. In determining a particular type of EMP environment one considers the nuclear detonation geometry and the observer position. These will determine the presence or absence of local nuclear radiation, current sources, conductivity, and other electromagnetic variables such as the presence of a conducting half-space such as ground or water. It is these conditions that an EMP simulator attempts to approximately reproduce either in some complete sense or in a sense for which the test results can be simply related to what would exist in the situation being simulated. Note that a special form of EMP referred to as system generated electromagnetic pulse (SGEMP) is also discussed from its simulation aspects in this paper; the paper by Higgins, Lee, and Marin in this issue discusses the general SGEMP phenomenon.

This leads to a (somewhat tentative) definition of (EMP) simulation. (EMP) simulation is an experiment in which the postulated (EMP) exposure situation is replaced by a physical situation in which:

1) the (EMP) sources are replaced by a set of equivalent sources which to a good approximation produce the same excitation (including reconstruction by superposition to the extent feasible) to the total system under test or some portion thereof as would exist in the postulated nuclear environment, and

2) the system under test is configured so that it reacts to sources (has the same Green's function) in very nearly the same way and to the same degree as it would in the postulated nuclear environment.

A(n) (EMP) simulator is a device which provides the excitation used for (EMP) simulation without significantly altering the response of the system under test by the simulator presence.

The reader will then note that proper configuration of the system under test with the simulator gives simulation. While most of our attention is devoted here to simulators per se, the system under test and its relation to the simulator are also important. In this regard it helps to have some understanding of the EMP interaction process; various papers in this issue discuss EMP interaction technology.

Since there are various levels of the system/environment interaction starting from the nuclear source as it first interacts with the system, we can define a concept of level of simulation. In this regard consider the relevant steps $(\mathrm{Env})_n$ in the EMP environment [143]:

$(\mathrm{Env})_1$	photons (γ and X rays) and neutrons,
$(\mathrm{Env})_2$	source electrons (produced by Compton scattering and photoelectric process by interaction of photons with surrounding medium or with the system itself) with accompanying ionization,
$(\mathrm{Env})_3$	source current density (electromagnetic result of a distribution of source electrons),
(Env_4)	electromagnetic fields (including potentials, etc., resulting from source current density and any associated medium conductivities),
$(\mathrm{Env})_5$	surface current and charge density (or current and voltage) at penetrations into system (relevant for cases of no sources within system envelope),
$(\mathrm{Env})_6$	surface current and charge density (or current and voltage) at penetrations into a second layer of the topological shielding of the system (relevant for cases of no sources within second shielding layer),

etc.

Let n designate the first interaction of the nuclear environment with the system of concern [144], [145]. For a system in a nuclear source region $n = 1$; for a system away from a nuclear source region with EMP fields propagating to it $n = 4$. Let us designate the type of source used in the simulation according to this same list by n'. Define the level of simulation removal by $l = n' - n + 1$ with $l = 0$ specially defined so that we have:

$l = 0$	the real thing, i.e., no simulation at all,
$l = 1$	replacement of the very first thing incident on the system by something of the very same kind (i.e., $n' = n$),
$l = 2$	introduction of sources at next physical step in interaction sequence from nuclear environment (e.g., photons replaced by equivalent resulting electrons, or incident fields replaced by current and charge densities on system exterior),

etc.

Level 1 is then in general the highest quality simulation in the sense that it makes the fewest assumptions about the interaction of the nuclear environment with the system. Successive levels make progressively more such assumptions. With these definitions we can appropriately speak of first removed simulation, second removed simulation, etc., to denote the relation of the type of simulation under consideration to the nuclear environment being simulated.

Most of the discussion concerns what can be referred to as system level simulators which include those which excite the entire system in a way which is directly relatable to the EMP environment of interest. Not included in this paper are those "simulators" used to test pieces of the system such as racks, "black boxes," or "critical circuits." In terms of environment levels $(\mathrm{Env})_{n'}$ being produced by the simulator on the system, this paper then includes $1 \leqslant n' \leqslant 5$.

The various types of EMP simulators can be categorized according to what might be termed their dimensionality.

a) *Three Dimensional (or Volume):* The most general case has distributed volume sources which vary over the test volume as do the resulting fields; there may be special boundary conditions around some volume of concern as well.

b) *Two Dimensional (or Surface):* If there are no distributed volume sources (source currents) around (and perhaps inside) the system under test then the incident fields are determined by boundary values on some surrounding surface (including perhaps a radiation condition at infinity). Such simulators rely on the electromagnetic uniqueness theorem relating surface boundary values to volume fields.

c) *One Dimensional (or Line):* Certain systems under test that are long and thin (although not necessarily straight) such as power lines, certain types of antennas, etc., and the response of which can be approximately described by an integral equation over a path in space, can have a special kind of simulator that recreates the incident tangential electric field over a narrow tube around this path.

d) *Zero Dimensional (or Point):* For (electrically) small test objects, including small penetrations on larger test objects, simulators can be designed which are also electrically small and produce approximately locally uniform electric and magnetic fields and perhaps source current density and/or conductivity. In special cases these may even reduce to an appropriate current or voltage applied to a penetration in the sense of a circuit port.

Specifically what distinguishes one type of simulator from another is its electromagnetic geometry, i.e., the way that it forms fields (and perhaps sources) in space in the vicinity of the item under test. A given simulator may utilize any of several electromagnetic sources. It is common practice (especially with parallel plate simulators, specific examples being ALECS and ARES) to have high voltage (multimegavolt) pulsers, repetitive pulse generators in the hundred kilovolt range, and continuous wave generators as well. As various categories of simulators have been added, names have been given to these categories such as hybrid, RES, TORUS, SIEGE, etc. Note that in some cases these category names are acronyms; these are to be distinguished from the names of specific simulators such as ALECS, ARES, ATLAS, EMPRESS, etc.

Specific EMP simulators have various performance limitations. The degree of such limitations needs to be quantified so as to be able to relate the system response in the simulator to its response in a nominal EMP environment. This leads to a concept of figures of merit for simulator designs. Such figures of merit compare various features of the calculated and/or measured performance with some ideal (preferably simple) electromagnetic environment. Such figures of merit allow one to trade off various compromises in performance to achieve a balanced simulator design within various constraints of money, time, etc.

One type of figure of merit refers to the electromagnetic fields produced by the simulator without any system of interest present. For the waveform, the rise time may be slower than desired, amplitudes smaller than desired, frequency spectrum less than ideal in various frequency bands, etc. The electromagnetic field distribution may also be deficient in that it may be not ideally uniform at low frequencies, or the early time arrival of the fields may deviate from an ideal type of wave such as a uniform plane wave.

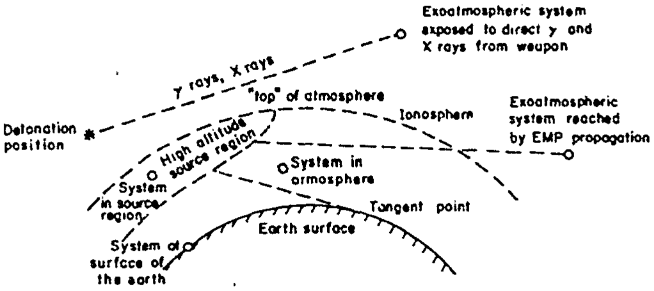


Fig. 1. High altitude burst geometry.

Another type of figure of merit refers to the interaction of the system under test with the simulator structure. The system under test scatters the fields incident upon it. These scattered fields in turn scatter from the simulator back to the system under test thereby changing the currents, charges, etc. induced on the system. This multiple scattering process continues indefinitely in time. In frequency domain various impedances associated with the simulator are changed by the presence of the system. This multiple scattering should be kept small so that amplitudes, complex resonant frequencies, etc. of the system response are not changed to some unacceptable degree. This usually means that the simulator must be sufficiently larger than the system under test or that the two must be sufficiently far apart depending on the simulator and system geometries. Within a nuclear source region this simulator/object interaction includes multiple-scattering effects of the X-ray, γ-ray, and neutron sources as well. Many of the references treat simulator/object interaction questions [18], [34], [47], [52], [60], [65], [66], [69], [73], [75]-[77], [80]-[82], [95], [105], [109], [112], [114], [120], [124], [127], [130]; such detailed calculations are beyond the scope of this note.

II. SIMULATORS FOR EMP OUTSIDE OF NUCLEAR SOURCE REGIONS

Of the different kinds of EMP environments, the most significant of these outside the source region is that in the air and on the earth associated with an exoatmospheric nuclear detonation. Fig. 1 shows the appropriate geometry. For simplicity let the system location lie in a line of sight to the detonation point (without passing through the earth). A nominal approximation of the incident waveform to be simulated would have a rise in the 10^{-8} s ballpark, an electric field peak amplitude in the 10^5 V/m ballpark, and a few hundred nanoseconds decay constant (let us say, exponential decay). Its Fourier transform would be fairly smooth and not roll off at low frequencies but have a low-frequency value corresponding to the complete time integral of a waveform with only one polarity. The actual EMP environment does cross over at some point in time for a given vector component, but the resulting low-frequency roll-off occurs at quite low frequencies. The environment to be simulated can usually be approximated as an incident plane wave. There is a significant reflection from the earth surface giving another approximate plane wave propagating upward. Note that the polarization of the incident wave can be at various angles depending on the detonation position, observer position, and the direction of the earth's magnetic field in the source region. This polarization changes somewhat with time during the pulse, but EMP simulators to date have given time independent polarization which in some simulators can be changed from pulse to pulse by an appropriate reconfiguration.

EMP simulators for outside of source regions can be divided into two classes: those which simulate an approximate free-space plane wave on the system, and those which simulate such a plane wave plus the reflection from the surface of the earth. For systems that are in the air or above the atmosphere the time delay between the incident wave at the system and the subsequent arrival of the reflection from the earth surface can be quite large. In such cases it is common practice to simulate a single uniform plane wave arriving on the system with an appropriate simulator designed to fulfill this requirement. For systems that are on or near the surface of the earth the reflected wave from the earth surface is an important factor in the simulation and can be produced by various simulator types. Of the various types of EMP simulators discussed in this section the reader will note that in some cases an EMP simulator category applies to simulating an incident plane wave with or without earth reflection depending on how it is used or on certain alternatives in its configuration.

A. Dipole Simulators

The class of EMP simulators that are basically dipoles is useful for EMP simulation in cases where the simulator is to be far from the system under test compared to the size of the dipole structure [7], [25], [29], [30]-[33], [38], [40], [41], [44], [54], [56], [57], [59], [70], [72], [74], [79], [83], [88], [93], [98], [106], [113], [115]-[117], [122], [134], [146], [147]. In producing a radiated electromagnetic pulse the r^{-1} radiation field is limited in its low-frequency content. The low-frequency fields including r^{-1}, r^{-2}, and r^{-3} terms are dominated by the dipole moments, both electric and magnetic, of the simulator. For finite energy in the pulser one can achieve a non-zero (but only finite) late-time dipole moment. One of the most significant design features of such dipole simulators is the magnitude of the late-time dipole moment.

Fig. 2 shows the basic types of dipoles. In an electric dipole simulator one maintains a late-time charge separation (if one starts from no charge separation). A magnetic dipole simulator would correspondingly be designed to have a late-time current flowing in a closed path around an area. By combining an electric dipole moment p with a magnetic dipole moment m at right angles to each other and related by the speed of light then in the direction p X m the fields are TEM at all frequencies for which the dipole moments give the only significant contribution to the fields at the r of interest [70]. A large pulse version of this which uses a ground plane is a simulator type referred to as DILEMMA (*di*pole *l*arge *e*lectric and *m*agnetic *m*ixed *a*ntennas). The smaller CW version of the concept is referred to as MEDIUS (*m*agnetic and *e*lectric *di*pole *u*niform *s*imulator). Note that in using images with a ground plane the possible polarizations of the resulting equivalent dipole moments are limited. Furthermore such objects are described as dipoles only for distant observers (distant compared to the antenna size) and low frequencies (with wavelengths large compared to antenna size).

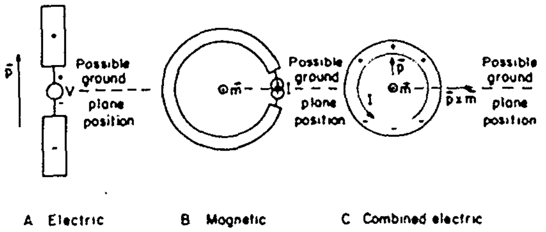


Fig. 2. Types of dipoles.

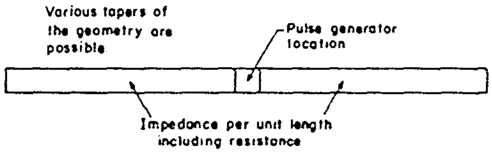


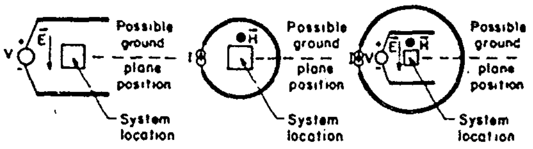
Fig. 3. Large impedance loaded electric dipole shaped roughly like a long, thin rotationally symmetric structure (RES).

A common type of dipole simulator is RES (*r*adiating *E*MP *s*imulator) as shown in Fig. 3. This type of simulator is a large electric dipole shaped roughly as a long, thin rotationally symmetric body which may taper along its length in various ways. Impedance loading (typically resistance) is used to dampen oscillations on the structure. The RES 1 type of simulator approaches 100 m long, and has been used with capacitive pulse generators approaching 2 MV. This type of simulator has been realized in more than one configuration with helicoptor suspension.

Another realized type of dipole simulator is a resistively loaded circular cone mounted on a ground plane. Such a vertically polarized electric dipole has been constructed as ACHILLES I, and a larger one, ATHAMAS II, with about a 40 m height, 40° half cone angle, and 5MV pulser is under construction, (both on Kirtland AFB). Another example is the NAVES II under construction with a 20 m height operated by Naval Surface Weapons Center. These radiate a damped, azimuthally independent waveform.

B. Other Simulators for Systems Far from the Simulator Structure

In some cases one may be willing to ignore low-frequency characteristics for purposes of designing some special purpose simulators which emphasize the high-frequency characteristics of a waveform by giving the simulator various directional characteristics. One type of directive pulse radiator is an array of pulsers wired together and triggered in a sequence which launches a wave (let us say plane or spherical) in a desired direction [53], [121], [123]. Such a simulator could for some complex frequencies be approximately focused on the system so such a technique could be appropriately labelled FOCUS (*f*ast *o*mnidirectional *c*oherent *u*ltra *s*imulator). Needless to say, such a technique has many limitations when compared to quality EMP simulation.



A Electric field (and current density) B. Magnetic field C. Example of combined electric and magnetic static fields

Fig. 4. Static simulators.

C. Static Simulators

Another class of EMP simulators can be thought of as static simulators [91], [136]. This class could also be termed zero-dimensional or point simulators. Here the system under test is very close to or even within the simulator structure. The basic limitation of a static simulator is that frequencies are sufficiently small so that the corresponding wavelengths are large compared to the simulator structure (including the system location as well) so that the low-frequency or quasi-static form of the fields is applicable. Ideally, the incident fields produced by such a simulator are uniform in the vicinity of the system.

Fig. 4 shows a few simple designs for this class of simulators. The simplest are those which produce a single component of electric or magnetic field incident at the system. However, up to six orthogonal electric and magnetic field components can be produced with separate waveforms if desired. Fig. 4(c) shows a case with one electric and one magnetic field component produced by such a simulator. Resistive walls and guard rings can be used for electric field cases and multiple coil designs can be used for magnetic field cases. One should take care in combining various incident field components that each portion of the simulator structure producing each field component does not significantly distort some other desired field component.

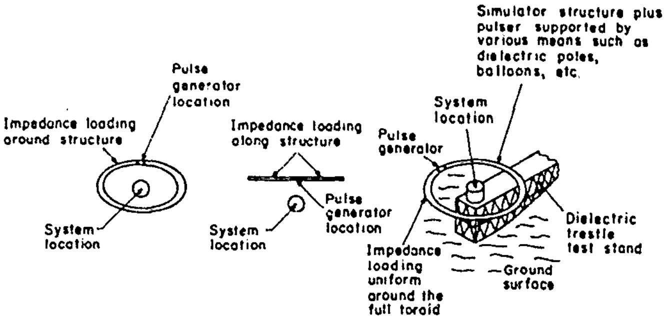
This type of simulator is appropriate for driving very small systems or penetrations (small antennas and apertures) on highly conducting surfaces of larger systems [144], [145]. In the latter case only the electric field normal to the surface and the magnetic field parallel to the surface are of interest; this concept is referred to as FINES (*f*inite *i*ntermediate *n*uclear *E*MP simulator).

D. A Class of Hybrid Simulators

Now let us briefly consider a class of hybrid simulators formed by combining various features of radiating simulators and static simulators. For this simulator concept to apply, the system under test should be within or quite near the simulator structure. The basic concept of this class of hybrids can be summarized in three basic characteristics [30], [31], [48], [51], [61], [67], [68], [99], [119], [141].

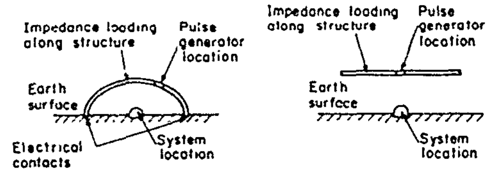
1) The early-time (high-frequency) portion of the waveform reaching the system is radiated from a relatively small source region compared to the major simulator dimensions.

2) The low-frequency portions of the waveform are associated with currents and charges distributed over the major dimensions of the simulator structure. This structure either surrounds the system or is very close to it.

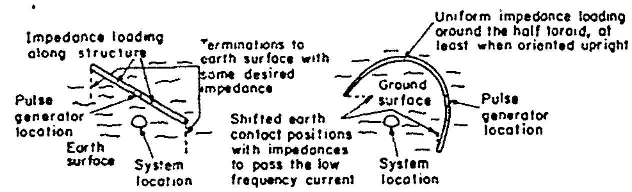


A General concept with conducting path around system B. General concept with path around system via electric flux (capacitance) C. Example. TORUS in a full toroid configuration

Fig. 5. Class of hybrid simulators without earth reflection as part of simulation.



A General concept with conducting path around system B General concept with path around system via capacitance between simulator structure and earth surface



C. Example: thin structure above and parallel to ground surface D. Example: TORUS

Fig. 6. Class of hybrid simulators with earth reflection included as part of simulation.

3) The structure is sparse so that most of the high-frequency energy radiates out of the simulator without reflecting off the simulator structure. The structure is also impedance loaded (including resistance) to further reduce unwanted reflections in the simulator. This also dampens oscillations in the intermediate frequency region where the simulator dimensions are comparable to an appropriate fraction of a wavelength. At low frequencies the structure reflection should become larger smoothly to make the fields transition over to the static field distribution smoothly.

As with various other simulator types, this class of hybrid simulators may be designed to be operated in a "free space" mode as shown in Fig. 5, or with a ground plane or earth surface as part of the simulator as shown in Fig. 6.

Consider first the type of hybrid simulator for producing a plane wave of some polarization and direction of incidence in the vicinity of the system without a reflection from the earth surface as part of the simulation as in Fig. 5(a). By using an impedance per unit length around the structure which is designed to be a nonzero (but finite) frequency-independent resistance per unit length at low frequencies, then the electric and magnetic fields incident at the system at low frequencies have the same frequency dependence. By choosing the value of the low-frequency path resistance appropriately the E/H ratio for the low-frequency fields incident at the system can be made to approximate the free space impedance of about 377 Ω [99]. If the path does not go around the site, such as in the case shown in Fig. 5(b), the static fields from the simulator structure can still encompass the site with large low-frequency electric fields. However, the E/H ratio for the low frequency fields is proportional to $(i\omega)^{-1}$ where ω is the radian frequency. Resistive and other impedance loading can still be used to smooth out the intermediate frequency response. However, the low-frequency limitation discussed above makes this type of hybrid simulator in general inferior to the type for which a low-frequency resistive path extends around the system under test.

A particular type of hybrid is TORUS (*t*ransient, *o*mnidirectional, *r*adiating, *u*nidistant, and *s*tatic) which is shown in Fig. 5(c) in a full toroid configuration as appropriate for simulating an incident plane wave without a reflection from the earth surface [48]. In a real simulator a test stand, such as a dielectric trestle, would hold the system high above the earth surface in the middle of the TORUS type of simulator. This reduces the effects of earth reflection to some desired maximum perturbation of the fields incident upon the system depending on the height above the earth surface. The impedance loading around TORUS is resistive, at least at low frequencies, and is approximately uniform around the structure so as to give more symmetry to the circular structure and thereby simplify the analysis of its performance. This type of simulator can give all angles of incidence and polarization for the wave incident on the system in approximating an incident plane wave. As such it is one of the highest quality simulators in this class of hybrids. With a capacitive pulse generator both electric and magnetic field waveforms can have both the early-time and low-frequency characteristics desired of pulsed incident EMP waveforms.

A more important class of hybrid simulators is that which includes a ground reflection as part of the simulation. The class that has only a single plane wave with no ground reflection can be compared with TEM transmission lines (to be considered later), in which case a transmission-line simulator can be made of rather higher quality and better efficiency. However, if the reflection from the earth surface is to be included in the simulation then hybrid simulators have much to offer in both quality of electromagnetic fields and relative practicality of construction. The TORUS simulator concept was originally developed as a quality type of simulator for this application; a version in the 100 m diameter and 5 MV pulser range has been realized.

Fig. 6 shows some of the features of this class of hybrid simulators for simulating an incident plane wave EMP with a reflection from the earth included as a desired and important part of the simulation. First we have in Fig. 6(a) the general case in which the simulator structure forms an impedance-loaded conducting path around the site where the earth is included as a part of this path. By appropriately choosing the impedance loading in the simulator structure so that it has an optimum resistive value at low frequencies, the E/H ratio can be chosen for the incident fields including ground reflection in the vicinity of the system under test. Note that the incident fields plus ground reflection for an infinite incident plane wave and a homogeneous earth half space result in an electric field perpendicular to the earth surface at low frequencies. The low-frequency magnetic field in such a hybrid simulator may not be parallel to the earth surface in the absence of the system because of the nonuniform characteristics of the fields in a finite size EMP simulator, as well as nonuniformities in the properties of the local earth. However, by judicious configuration of the current path through the simulator conductors and loading impedances the low-frequency vertical magnetic field can be made rather small over limited regions of the earth surface (in the absence of the system).

In Fig. 6(b) there are no earth contacts. As discussed in the case for which the hybrid simulator has no closed conducting path around or near the system, the low-frequency E/H is not constant at low frequencies. The same conclusion applies in the case that a reflection from the earth surface is included if there is no such closed conducting path. In this respect the general hybrid type in Fig. 6(a) is superior to that in Fig. 6(b).

Fig. 6(c) shows a common type of hybrid simulator which has basically the geometry of a thin structure above and parallel to the earth surface [51]. Actually the structure may have some taper to it, usually in some symmetrical fashion with respect to the pulse generator. Note that by including impedances at each end to connect the ends to the earth surface this simulator is of the type in Fig. 6(a), while if the ends are not brought into contact with the ground this simulator is of the type in Fig. 6(b). This type of simulator with the system under test in near proximity or inside it would certainly not be classed as a dipole. Nor would it be classed according to the geometry of only a small region around the source (which might be a bicone for instance). The overall electromagnetic geometry including system location, closeness of the earth surface, connections to the earth, and impedance loading distribution is what characterizes this type of hybrid simulator.

One can mention several important simulators of this hybrid variety (including earth surface) which have been built including EMPRESS and NAVES I operated by Naval Surface Weapons Center, TEMPS at Harry Diamond Laboratory, and ACHILLES II and ATHAMAS I at Air Force Weapons Laboratory.

E. Guided Wave Simulators

Another important type of EMP simulator for producing an EMP environment appropriate to outside the source region is guided wave simulators. The concept here is to use some waveguiding structure which is basically two dimensional, or better described by two orthogonal coordinates, to propagate a wave in the direction of the third orthogonal coordinate. The wave is usually TEM (or approximately so) and propagating in air with metal conductors typically forming a large part of the simulator structure. The simulator structure forms part of the boundaries for the guided wave and so this class of simulators can also be referred to as bounded wave simulators. Such a waveguiding structure is chosen for its ability to control the field distribution in some approximately ideal form for all frequencies of interest from wavelengths small to large compared to cross-section dimensions.

A very important class of such simulators are uniform TEM transmission lines including both cylindrical and conical transmission lines [1], [2], [4]-[6], [11], [15], [16], [20], [24], [28], [39], [45], [49], [55], [63], [71], [78], [84]-[87], [89], [90], [92], [94], [97], [100]-[102], [104], [107], [108], [111], [118], [131]-[133], [137], [139], [140], [142], [148]. Such structures have characteristic impedances which are independent of frequency and position along the direction of propagation for the TEM mode. As such in the TEM mode, time-domain waveforms can be propagated without distortion at the speed of light on such simulators. While the TEM wave on such structures is in general nonuniform in that the fields distribution is a function of the cross section coordinates, still over a limited volume of space the TEM fields can be made quite uniform over the cross-section coordinates. In the case of a cylindrical transmission line the amplitude of the TEM wave does not vary along the direction of propagation for a fixed retarded time. For a conical transmission line the amplitude does vary for fixed retarded time as $1/r$, where r is the distance to the apex of the two or more conical conductors. If r is sufficiently large; however, the variation of $1/r$ over a limited volume of space can be made as small as one wishes. Thus over some limited volume of space where the system is to be placed for testing, an incident free space plane wave can be approximated quite well. This volume is usually termed the working volume, and this working volume concept applies to some other EMP simulator types (such as the class of hybrids discussed previously) as well.

Much detailed work has been done on this transmission line type of simulator and various design options are possible for the design details. Usually two plate type designs are employed, at least for large simulators, because of their efficiency in small cross-section dimensions for a given working volume and in correspondingly smaller pulser voltage for a given electric field. However, three plate geometries (usually with outer plates connected together at the pulser) have been used. Various other geometries such as two wires, four wires, etc., as well as curved plate geometries are possible also. Note that the highly conducting plates are usually approximated by wire grids or meshes, at least for the large simulators.

Consider two parallel finite-width plates (ideally perfectly conducting) or one plate of finite width parallel to a second plate ideally infinitely wide. Either of these cases gives a cylindrical transmission line. This is shown as the center section of an EMP simulator in Fig. 7. Having a cylindrical transmission line, the problem is how to launch the appropriate TEM wave on it. One of the simplest ways to achieve this is to make an input transition consisting of a conical transmission line which matches the conductors at the beginning of the cylindrical transmission line. This connects to the pulser at a position where the spacing of the two (or more) conical conducting plates is rather small. The spacing at the pulser plus the pulser characteristics determine the characteristics of the TEM and higher order modes on the conical transmission line; generally quite good TEM characteristics can be obtained on the conical transmission line. In matching the conical transmission line to the cylindrical transmission line, quite good TEM characteristics can be obtained on the cylindrical transmission line provided the conical one is long compared to its cross-section dimensions. Quite a high-frequency response for the TEM mode is obtained this way, and this is due to the close match between spherical and plane wave modes at the junction, since the principal difference is attributed to phase [5], [89].

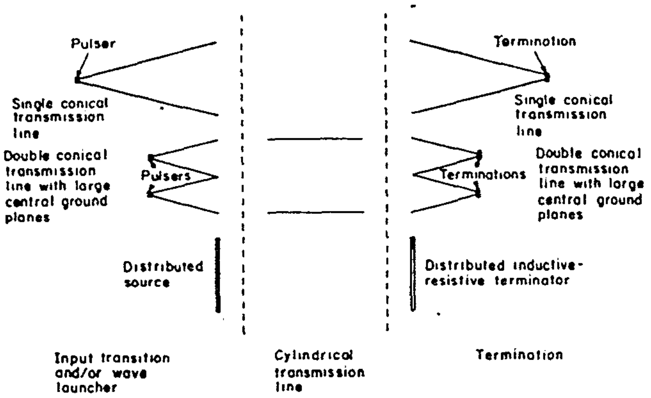


Fig. 7. Some optional designs for two-parallel-plate transmission line simulator: View parallel to plates and perpendicular to direction of propagation.

Note that two conical transmission lines can be used in series driving the cylindrical transmission line provided the two central plates are effectively infinitely wide with both plates of the cylindrical transmission line of equal finite widths and symmetrical positions [5]. The modal field distributions make a good match due to the symmetry of the problem in this case. Three or more input conical transmission lines connected together have problems makeing a good TEM field match.

A large distributed source array can be used in place of the input conical transition, but the pulsers are now physically much larger and it is difficult to match the TEM mode of the cylindrical transmission line without making the source array much larger than the cross section of the conductors of the cylindrical transmission line. A large distributed source is practically made from many small sources so that the transit time between them is acceptably small so as to obtain good high frequency performance. Generally such a distributed source is not as good as a conical transmission line input transition with small angle of spread between the conductors. However, for very large voltages, the pulser output geometry has to be large enough so as to not break down the air or other insulating medium (with wave impedance approximating that of air) when the pulser is discharged. Thus for large voltages one may construct a distributed source pulser array which is made as small as practical and matches onto a conical transmission line, which leads in turn to the cylindrical transmission line.

The simulator is terminated by one or two conical transmission lines leading to a small resistive termination. Such output transitions are basically the same as the input transitions. One can also use a large distrubuted admittance sheet as a termination at the end of the cylindrical transmission line. Such a termination should not consist of a purely frequency-independent resistance. The high frequencies pass into the space behind the termination, and the termination should behave more like free space for such high frequencies. A simple approximation for such a termination consists of a series inductor and resistor for each incremental area. This inductance can also come from the resistor design itself and/or the spacing between the resistors. Again for high voltages a real termination needs some size, and so a combined small LR termination with a conical output transition is very practical in such a case. Note that in some cases it is quite possible for the input and output portions to be directly connected without going through a cylindrical transmission line and still have a working volume in the simulator.

If capacitive pulse generators are used (which are not loaded by low impedances at low frequencies such as by driving them through pulse transformers) then it is quite practical to obtain fast-rising large-amplitude waveforms with smooth decays. The waveforms can then be designed to have the approximate desired frequency content throughout the spectrum of interest from essentially zero up into the range of 100 MHz or so depending on the high-frequency characteristic of the pulser outputs.

Two important examples of existing parallel plate simulators are ALECS (about 1.3 MV pulser, 13 m plate spacing, 25 m top-plate width, 115 m length) and ARES (about 4 MV pulser, 40 m plate spacing, 40 m top-plate width, 189 m length) on Kirtland AFB, both with vertical polarization for testing primarily missiles. Under construction at the same location is ATLAS I (two pulsers each about 4 MV, 105 m plate spacing, 75 m central-ground-plate height, 34 m plate width, 410 m length) with horizontal polarization for testing aircraft as illustrated in Fig. 8. Note the presence of the large wooden trestle (about 36 m at highest) which is to be essentially electromagnetically invisible while supporting the test object. A comparable transmission line simulator, ATLAS II, has been designed for vertical polarization. All of the above examples have horizontal propagation. These examples illustrate the evolution and increasing sophistication of EMP simulator design. Looking back, this author first designed ALECS as a two-plate structure with a flat ground plane, then gave ARES a ground "plane" with two bends to reduce the length (as also in ATLAS II), and then gave ATLAS I a dual launch (this simulator being required to test very large objects), a specially contoured earth, and an angled output transition to allow aircraft entry. This sequence evolved from a yet earlier design of R. Partridge for ALECS as a three-plate structure for instrumentation development.

There are other less important types of guided wave simulators for simulating EMP outside of source regions. For example, one can guide a wave along the earth surface with a conducting boundary placed above and parallel to the earth surface. This has an important role for partially simulating EMP in source regions at the earth surface. However the high-altitude EMP incident on the earth surface can be much better simulated by a hybrid type of simulator, such as TORUS, only if a relatively small surface area on the earth surface needs to be illuminated. Such a guided wave simulator would be useful for simulating the EMP propagated in a ground wave to a system at the earth surface.

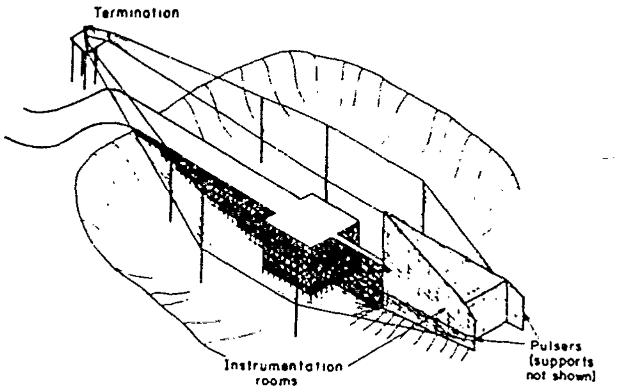
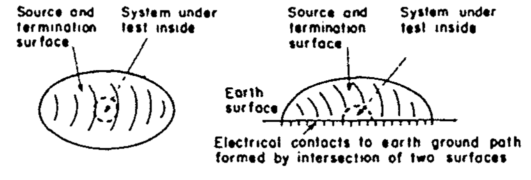


Fig. 8. ATLAS I.

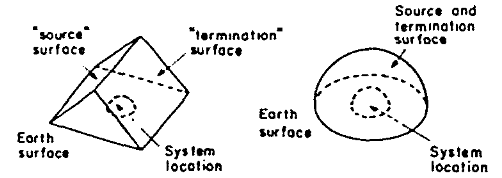
Here one should also mention that for transmission line simulators certain types of systems may operate tied to conducting ground planes; in such cases one of the plates of the transmission line can be that ground plane, and the system can be appropriately tied to it. However, the direction of incidence and polarization of the incident wave (with respect to the system orientation) are somewhat restricted. In the difficult task of including the effects of the finitely conducting missile plume in the simulation, sometimes the rocket nozzle region of the missile is attached to the simulator structure so that the image of the missile on the other side of the conducting plate acts as a plume of limited dimensions. By including another pulser in the connection from nozzle to plate, the current can be increased and its waveform shaped to approximate a current waveform that one would calculate for some assumed plume geometry and conductivity. This is a localized appendage simulator appropriate for use in conjunction with a transmission line simulator. This has not been treated in the Sensor and Simulation Notes as of yet but will be dealt with in some future note.

F. Simulators with Distributed Source and Termination Surrounding the System

Another class of simulators pertaining to EMP outside of nuclear source regions can be obtained by a simple application of the uniqueness theorem for the solution of electromagnetic boundary value problems in linear media without sources [58]. Consider a uniform TEM plane wave in some volume of free space bounded by a closed surface. Determine the component of the electric field or magnetic field tangential to the bounding surface associated with the assumed plane wave. Reproduce this tangential electric or magnetic field on the boundary, including its temporal and spatial distribution on the boundary, and the original plane wave is reproduced. This property, of course, holds for all sorts of electromagnetic distributions (as long as they satisfy Maxwell's equations) and various types of media in the volume of interest. This type of simulator is then another kind of bounded wave simulator. Again note that the test object should be small enough that its



A. General concept without reflection from earth surface
B. General concept with earth reflection (or special case of wave propagating along earth surface)



C. Example prism geometry
D. Example: hemispherical geometry

Fig. 9. Distributed source and termination enclosing system.

scattered fields are not significant when interacting with the simulator.

Typically, the tangential electric field is what one would specify on the boundary. A low-impedance electric field source can be approximately realized at high frequencies (early times) by a distribution of capacitive pulse generators with timed switches. However, not all portions of the bounding surface are sources. If one specifies the appropriate tangential electric field on the surface, then electromagnetic fields are produced outside the surface as well. The difference between the internal and external tangential magnetic fields determines the surface current density on the surface of interest. A comparison of the tangential electric field and surface current density on the surface determines at each frequency whether that portion of the surface is ideally a source or a sink for electromagnetic energy. Thus in general, lossy impedances must be included in the surface. The surface around the volume of interest (which will contain the system to be tested) is thus a combined source and termination surface. This general concept is indicated by a sketch in Fig. 9(a).

This type of simulator which produces an approximate uniform plane wave can be readily generalized to include a plane wave with a reflection from the earth surface as indicated in Fig. 9(b). There is an approximation involved in this procedure when a reflection from the earth surface is included because the fields penetrate into the ground. As long as the frequencies are high enough that the radian wavelength or skin depth (as appropriate in the local earth) is sufficiently small compared to the dimensions of the simulator surface where it contacts the earth surface, then the approximate division into an interior and an exterior volume still applies. For much lower frequencies this division does not apply so well, particularly as regards the magnetic field distribution or even the electric field in the earth. At such low frequencies, quasi-static approximations for above the earth surface can be used to better analyze the simulator performance.

Fig. 9(c) and (d) show some possible specific geometries for such a simulator. However, such simulators may not be efficient or perfectly realizable in practice. Perhaps their important feature is the theoretical concept which is helpful for understanding EMP simulators in general. For example such considerations apply to launching and terminating TEM waves on parallel plate simulators and to launching spherical waves on bicone-like sources on hybrid simulators and certain types of radiating simulators.

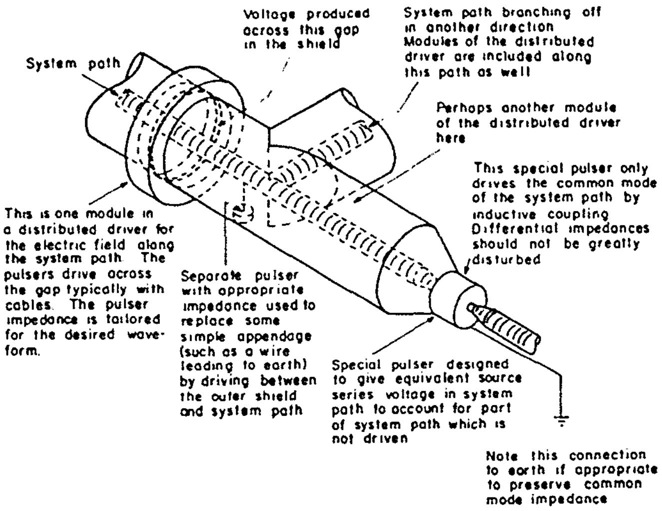


Fig. 10. One-dimensional or line simulator.

G. One-Dimensional Simulators

As briefly mentioned in Section I, a one-dimensional or line simulator is most appropriate for use with a system which can be approximately localized to a one-dimensional path [91]. This system path is idealized in Fig. 10 as a thin tube (compared to lengths of interest) which contains the system structure. This tube is the volume on which the EMP is simulated. For example the system may be a set of power lines with transformers, lightning arrestors, etc., at some height above the earth surface. Since we are assuming that the tube diameter is small compared to radian wavelengths of interest we can use thin-wire concepts and refer to a system path along the center of this tube.

If one were to analyze the current flowing in this tube, one might set up an appropriate electric-field integral equation for the current or currents flowing in this tube using thin-wire approximations. In such an integral equation the driving source is the incident electric field parallel to the thin tube. The incident electric field perpendicular to the system path can only drive short conductor segments, and is neglected in this type of simulator. Thus one of the requirements for this simulator is to produce the desired electric field incident on and parallel to the system path. This can be done by a number of modular pulsers inductively coupled to the system path as shown in Fig. 10. Together such pulsers and inductive couplers form a distributed driver which impresses the tangential electric field along the system path where each pulser is triggered at its own appropriate time with waveform changes as desired. The spacing between drivers along the system path should be small enough that transit times between adjacent ones are smaller than the smallest times of interest. However, the driving technique must not interfere with differential mode propagation in the system tube nor with the common-mode propagation along the system path. Thus the distributed drivers must present a sufficiently small common mode source impedance, let us say, by adding a resistive impedance in parallel with a low inductance.

Note the outer conducting tube surrounding the system path as indicated in Fig. 10. This ties together the distributed drivers thereby making them more efficient in confining the driving electric field nearer the system path. Furthermore it serves as a reference conductor for simulator operation and instrumentation. One should be careful that this outer conducting tube has a radius much larger than that of the system tube so that the common mode impedance associated with the system path is not grossly reduced from that associated with the system path when the simulator is not present. Viewed another way the Green's function should not be grossly changed. Considering the outer conductor and the central path as a transmission line (coax) with a characteristic impedance, then the reason that one does not grossly disturb the system impedances is that the impedance of a coax is only logarithmically dependent on the ratio of outer to inner radius. If initially the outer radius roughly corresponds to somewhat more than the height of the system path off the earth surface, let us say, then one can estimate the change in this logarithm and try to keep this change acceptably small.

There are occasions for which one would add pulsers with impedances between the system path and outer tube provided there were certain appendages (such as wires leading from lightning arrestors to earth) that one felt confident could be replaced by an equivalent generator to account for the incident electric field on the appendage and its effective impedance. For example it may be required that a waveform from such a pulser actually oscillates in some prescribed manner. Note that the system path may include branches as indicated in Fig. 10 but this presents no new kind of difficulty. The use of such branches in the system path represents an alternative way to include appendages to the system without directly replacing them in an equivalent circuit sense.

A special difficulty arises when the system tube must leave the outer tube of the simulator. This may arise in various cases. For example, power lines may enter a shielded enclosure. In that case the outer tube can be connected to the enclosure, and any appropriate equivalent generators with impedances to give the equivalent source presented by the enclosure can be included as a series voltage in the system path. Another example for power lines relates to their enormous length. The simulator must stop somewhere. As shown in Fig. 10 the outer tube can be connected to earth through a low inductance set of conductors and an equivalent generator can provide a series voltage to simulate the voltage presented at that position by the rest of the power line system were it to be illuminated by an electromagnetic pulse. Note that in general there may be several such extended conductor paths leading to a central enclosure.

While this type of simulator is inherently complicated it has certain advantages. First, it allows one to drive certain portions of large distributed systems up to high level ("threat" levels) and observe nonlinear response of various parts of the system. Furthermore, at least certain portions of such a simulator might be used to drive large distributed appendages of systems (such as power lines) while the localized system site was being driven by another simulator such as TORUS for example. In such a case it may be more a single pulser assembly providing an equivalent generator instead of a one-dimensional simulator.

Related to the one-dimensional simulator for driving appendages there are other concepts using equivalent circuits for the appendage. For replacing the appendage in the sense of the penetration to which the appendage is attached we have PORTAS (*p*enetration *o*f *r*adiation *t*hrough *a*perture *s*imulation). For partially simulating the scattering effects of the appendage on the major structure of the test object we have PALMES (*p*ulsed *a*ppendage *l*arge *m*obile *E*MP *s*imulator). For combining the scattering effects of the appendage with another (system level) simulator we have PLUS (*p*ulser *l*inked in *u*nited *s*imulator). These might be thought of as yet separate categories of simulators.

H. Some Comments Regarding Pulse Generators

Usually one wishes a fast rising unipolar waveform out of one's generator. This is usually supplied by a capacitive generator limited by switch inductance and some details of the Marx or other design for charging and switching the set of capacitors. Another less common type of waveform is that associated with the propagation of the simpler pulse through the ionosphere [91]. This gives a very dispersed oscillatory waveform requiring a rather complicated pulser with various potential realization techniques. Such pulsers can be used profitably with parallel-plate simulators.

III. SIMULATORS FOR EMP IN NUCLEAR SOURCE REGIONS NEAR THE EARTH SURFACE

In this section the source region is that for a near surface burst, and the location of interest for the system is near the earth surface either in the air, or in the lower medium (soil, rock, etc.), or both. The system location of interest with respect to the detonation position depends on the degree of mechanical hardness (to blast, shock, etc.) of the system. As one approaches the detonation position the EMP environment also becomes more severe. This geometry is illustrated in Fig. 11.

An EMP in a nuclear source region has important features which make it differ from an EMP outside such a source region. Important quantities associated with nuclear source regions enter Maxwell's equations and significantly alter the description of the EMP interaction with systems in such source regions [143]. In particular there is a source term consisting of a current density of high energy electrons and the air has a nonlinear time-varying conductivity. The lower medium has its conductivity increased as well near the surface, the fractional (time varying) increase depending on the type of medium (soil, etc.) and its ambient conductivity. The presence of the air conductivity is associated with a very important conduction current density term, which when added to the displacement current density gives one of the primary inputs to the current on electric-dipole types of structures if their load impedances are small; the source current density also has a direct input to

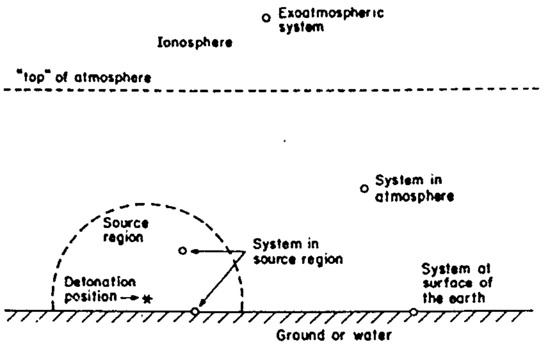


Fig. 11. Surface burst geometry.

such structures. Furthermore **E** and **H** are not simply related by the free space impedance, even in an incident wave sense (such as for a plane wave incident on the earth surface).

Needless to say these additional parameters in the EMP environment and the more complex relations among the various electromagnetic parameters make the associated EMP simulation problem considerably more difficult if all the additional features are to be accurately included in the simulation. In this context one considers various simulators which produce some of the desired electromagnetic parameters, but not all, at least for EMP simulation on large system sites. EMP simulators can produce part of the environment over all the site, or "all" of the environment over a small piece of the site (let us say, a small deliberate antenna), but generally not all the environment over all the site, at least not with present technology. The biggest problem is the radiation-driven source current density and the size of flash X-ray machine it would take to drive a site (with appropriate added electrical pulsers and boundaries) to levels appropriate to a surface burst at large close-in EMP levels. For near the "edge" of the source region such an X-ray machine might be thinkable for such a simulator. With time the technology for building large X-ray machines will likely advance significantly, but how far is hard to say.

A. Buried Transmission Line, Surface Transmission Line, SIEGE

Fig. 12 shows the concepts of the buried transmission line, the surface transmission line, and their combination which is referred to as SIEGE (*si*mulated *E*MP *g*round *e*nvironment) [3], [8]-[10], [13], [14], [17], [19], [21]-[23], [27], [35]-[37], [42], [46], [50], [62], [64], [110]. Historically, the buried transmission line was first emplyed to propagate the lower frequencies down into the earth in the vicinity of a buried test object near the ground surface. The vertical rods in the earth guide a lossy TEM wave propagating downward. At the bottom of the rods the wave is reflected, but the severe attenuation avoids significant resonant effects. Low frequency considerations require that the depth of the rods d be larger than the "plate" spacing l, and several times the depth of the test object. At the top of the transmission line some current path over the site is provided to connect the two rod arrays to the source (s).

For higher frequencies one can use a surface transmission line consisting of a conducting plane (say a wire grid) above the earth surface which guides a wave over the earth surface. By appropriate choice of the height h, one can compromise between an acceptably small attenuation of the high frequency wave and efficiency in obtaining large fields from the electrical pulsers. One can use wave launchers and terminators of a variety similar to those discussed in Section II-E to complete the high-frequency portion.

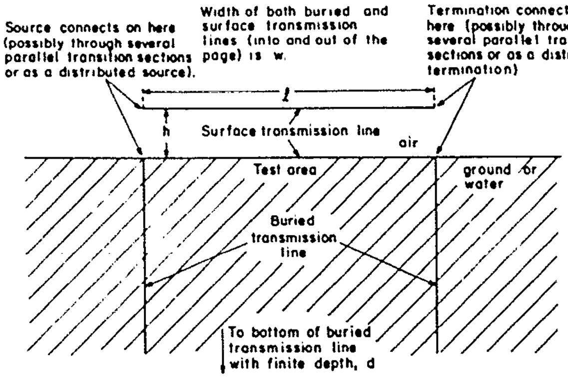


Fig. 12. SIEGE: Combined buried and surface transmission lines.

By making the width w of both surface and buried transmission lines the same, and by joining the launcher and terminator to the buried transmission line, a quite wide-bandwidth structure is achieved. Such a SIEGE simulator can be made to simulate the magnetic field close in toward a surface burst. However, the electric field and current density associated with the nuclear source region are not well simulated. Below some number of γ-ray mean free paths into the earth this limitation is not significant. This type of simulator has been used quite often.

B. Simulators with a Low Conductivity Medium Plus a Distributed Source and Termination Surrounding the System

One way to achieve a conduction current density in the vicinity of the test object is to place a conducting medium of appropriate constant conductivity there to replace the surrounding air. If one then attempts to propagate a wave through this medium, there will be such a current density of the form $J = \sigma E$ permitting one to simulate to some degree this phenomenon existing in the nuclear source region [58], [143].

Using the concept of enforcing the tangential electric field on a surface surrounding the test object and conducting medium as in Fig. 13, one can excite an appropriate (say plane wave) field distribution incident on the test object. However, the propagation medium should not be too conducting so as to excessively attenuate the higher frequency portions of the wave. This type of simulator has some similarities to that discussed in Section II -F.

C. DISCUS

Another type of simulator for the close-in EMP near the earth surface is DISCUS (*di*stributed *s*ource *c*onducting-medium *u*nderground-system *s*imulator) as illustrated in Fig. 14 [12], [26], [43], [91]. As with SIEGE, this type of simulator uses a buried transmission line to give the approximate

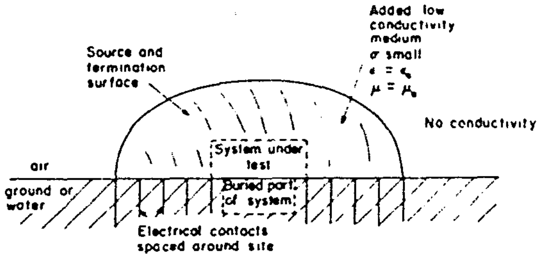


Fig. 13. Distributed source and termination bounding low-conductivity medium.

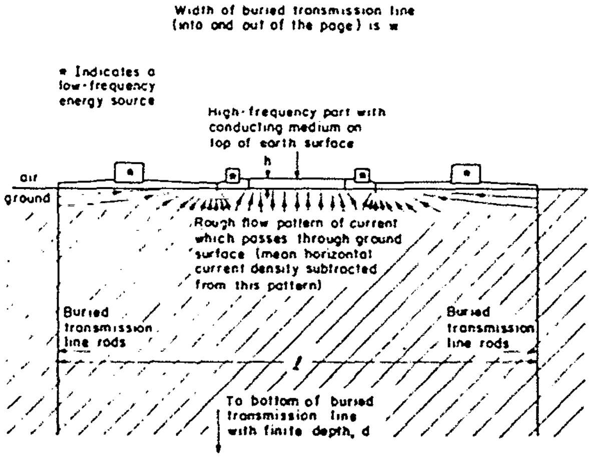


Fig. 14. DISCUS with both high-frequency finely gridded distributed source, driving conducting medium, and low-frequency coarsely gridded distributed source.

desired fields propagating down into the earth around the system site.

An essential new part of this type of simulator is the finely grided distributed source at a height h above the earth surface, with the medium of relatively high conductivity and thickness h spread out between the distributed source and the earth surface. This medium must be relatively thin (let us say a meter or so) to allow the high frequencies from the distributed source to propagate through it to the portions of the system near the earth surface. This distributed source with conducting medium is placed over those portions of the site at which the system is near the earth surface or even penetrates above the surface of the earth. If the system has large appendages above the surface which cannot be covered by this conducting layer then special parts of the simulator will need to be included for such appendages. Note that the added conducting medium should have permeability $\mu \cong \mu_0$.

The fast rising distributed source covering the added conducting layer is triggered in sequence across the site so as to give a propagation speed of c. Furthermore the amplitude driven by the successive generators can decrease slightly as one progresses in the direction of propagation, as is commensurate with the attenuation of the sources in a nuclear source region associated with the γ-ray mean free path.

The low frequencies are handled by additional pulsers which are connected into the distributed source as well as the rest of the site including a buried transmission line as discussed in Section III-A. This type of simulator is fundamentally more complex than SIEGE, but it has a simulated (albeit constant) air conductivity lowering the associated E/H ratio. It is still lacking the local radiation driven source currents and some of the associated complexities of the air and ground (enhanced) conductivity.

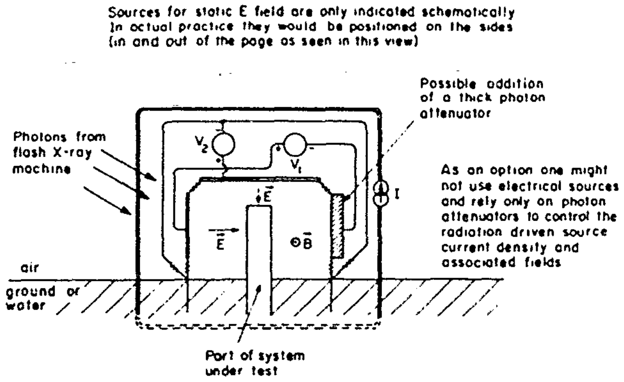


Fig. 15. Photons from flash X-ray machine driving small part of system at earth surface in static simulator configuration.

D. Static Simulators

As discussed in Section II-C, a static (or zero-dimensional or point) simulator is appropriate for producing low frequency fields on systems or system penetrations. Such simulators can be designed to operate away from or in conjunction with ground planes (or low impedance media). As shown in Fig. 15 the various electric and magnetic field components can be separately produced with different waveforms if desired.

In using static simulators for simulating the EMP in a nuclear source region one can readily add the conduction current density (parallel to the electric field) and the associated conductivity [91]. A medium of appropriate constant conductivity is simply added around the system or system penetration (or perhaps inside the system as well) in direct electrical contact with the conductors associated with the electric field pulsers. This of course lowers the impedance the electric field (and current density) pulsers must drive. The loops driven by the magnetic field pulsers need not be in contact with the added conducting medium. For a given size of simulator as the conductivity of the added medium is increased, the maximum operating frequency of the simulator as a static simulator is decreased.

As illustrated in Fig. 15, a photon (simulated γ-ray) source can be included with such a simulator to give more complete local simulation. With this addition all the important sources and fields are present (although over only a small volume of space) at least for the higher photon intensities.

E. One-Dimensional Simulators

As discussed in Section II-G, a one-dimensional simulator might be used. Here one could add a conducting medium around the one-dimensional path of interest, filling the surrounding tube. Photon sources can also be included, but their intensity is limited by the required exposure area.

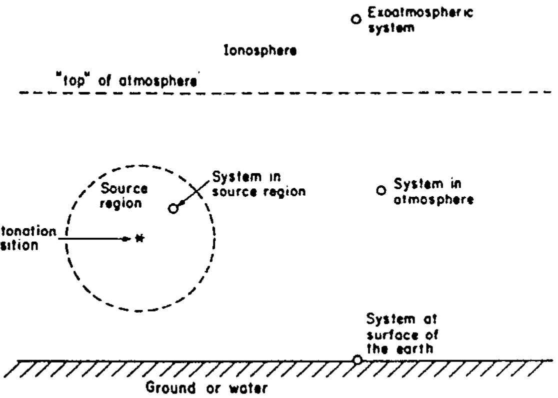


Fig. 16. Air burst geometry.

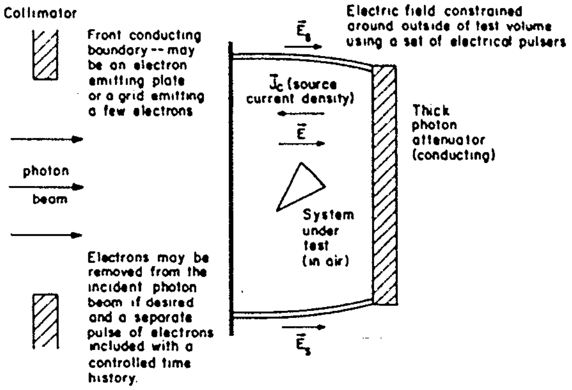


Fig. 17. Photon driven simulator with controlled boundary conditions.

IV. SIMULATORS FOR EMP IN NUCLEAR SOURCE REGIONS IN AIR

In this section the nuclear source regions of interest are in air and the systems of interest are not close to the ground surface as illustrated in Fig. 16. Generally speaking, the range of interest for the source photons and current density is toward lower amplitudes than one may consider for systems near the surface of the earth which may be designed to withstand large overpressures. While the source regions of interest include those resulting from surface bursts, air bursts, and high-altitude bursts, the systems of interest are what are generally termed inflight systems such as missiles and aircraft which cannot be very close to a nuclear detonation without sustaining mechanical damage. The fact that the system is not near the earth surface gives different characteristics to the field distribution illuminating the system.

Source regions in air cover a variety of altitudes, and thus a variety of air densities. Different altitudes thus imply different ranges for the high energy electrons, and different amounts of turning of the high energy electrons associated with the geomagnetic field. The electron mobility and other parameters influencing the air conductivity also vary with altitude.

As in the previous section, one can consider EMP simulators for this type of environment which are driven by electrical pulse generators or those which include high energy photon pulse generators. Not much work has been done to design and build specific simulators of this type but there are various approaches which can be used.

A. Simulators with a Low Conductivity Medium Plus a Distributed Source and Termination Surrounding the System

In Section III-B, this type of simulator was discussed for a source region near the earth surface (Fig. 13). The present case differs from that in Section III-B in that the present has no local earth surface to contend with. One can then propagate a single approximate uniform TEM plane wave through the volume of interest with various polarizations and angles of incidence.

A related type of simulator consists of a TEM transmission line in a medium of low conductivity which is bounded on one end by a distributed source, and on the other end by an appropriate distributed termination. The system of interest would be placed "inside" the transmission line just as in the case of a transmission-line EMP simulator without such a conducting medium. Of course the system would be made to have electrical contact with the added medium of low conductivity.

B. Zero-Dimensional (Static) Simulators

Zero-dimensional (or point) simulators can also be used for simulating EMP in nuclear source regions in the air. This type of simulator has been discussed in Section III-D for the case of nuclear source regions near the earth surface. Of course, in the present case there should be a medium of appropriate constant conductivity included just as in the case discussed in Section III-D. Note that photon sources can be combined with this type of simulator as discussed previously.

C. One-Dimensional Simulators

One-dimensional (or line) simulators can also be used for simulating EMP in nuclear source regions in the air. The techniques are the same, and Section II-G and Fig. 10 can be referred to for more details. Note that in the present case a medium of appropriate constant conductivity is added inside and in contact with the outer conducting tube. This conducting medium should also be in electrical contact with the system located near the system path. In principle, photon sources can be included with this one-dimensional simulator except that the desired illumination volume may be excessively large.

D. Photon Driven Simulator with Controlled Boundary Conditions

Fig. 17 illustrates a rather complete form of simulation for use with small systems in air [91]. A photon pulse illuminates the system and surrounding volume. Emission of electrons from the front boundary and collection of electrons and photons at the rear boundary is controlled. At the side boundary (parallel to the photon propagation direction) the tangential electric field is controlled to match the corresponding situation for the fields on this surface in the real case. This is some source electric field provided by a set of electrical pulse generators appropriately configured near this surface. From another viewpoint such sources are used to compensate for the fringe

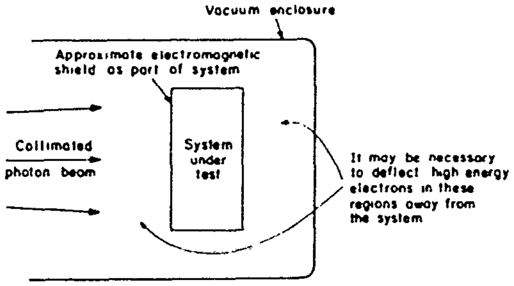


Fig. 18. Photons from flash X-ray machine driving an approximately electromagnetically closed system.

capacitance (or more general admittance) associated with the space outside the photon-illuminated test volume.

Various detailed parameters can also be controlled in such a simulator. These include pressure and temperature of the air and the ambient magnetic field. At low air densities, one may wish to delay the electron arrival with respect to the photon arrival by suppressing the electron generation by the photons at the front surface and supplying the high energy electrons later from a separate source. One may even wish to alter the electron trajectories in a manner similar to that which occurs at high altitudes due to the geomagnetic field.

V. SIMULATORS FOR SYSTEMS GENERATED EMP (SGEMP) IN EXOATMOSPHERIC REGIONS

Exoatmospheric systems such as satellites have a special type of EMP environment when exposed to the γ and X rays from an exoatmospheric nuclear detonation. This is one of the situations illustrated in Fig. 1. This is the SGEMP associated with the electrons ejected from the system materials. The gas density in the surrounding space is extremely small, and so one does not consider it conducting during the EMP in the usual sense of a conducting medium with $\mathbf{J} = \sigma \mathbf{E}$ where σ may be a matrix or even nonlinear. This special type of behavior of the electrons ejected from the system involves relativistic equations of motion for the electrons in the presence of the EMP fields.

A. Photon Driven Simulators (First Removed Simulation)

The most complete type of SGEMP simulation begins with photons replacing those of the postulated nuclear detonation. If pulsed photon sources such as flash X-ray machines are used to illuminate the system and thereby eject the electrons, it is important that the pulsed photon source have photon numbers per unit area, spectra, and waveforms which reasonably approximate the γ and X rays from the nuclear detonation of interest.

If the system response is approximately only an interior problem because of a reasonably good outer shield, then the simulation problem simplifies somewhat. The significant sources to be simulated are on the system interior (whence this phenomenon in this case is also referred to as internal EMP (IEMP)). Then as illustrated in Fig. 18, one can put the system in an appropriate vacuum environment and illuminate it with photons with provision for entry of the photons to the system. It may be also desirable to cancel or alter the ambient geomagnetic field to which the system is exposed during the test.

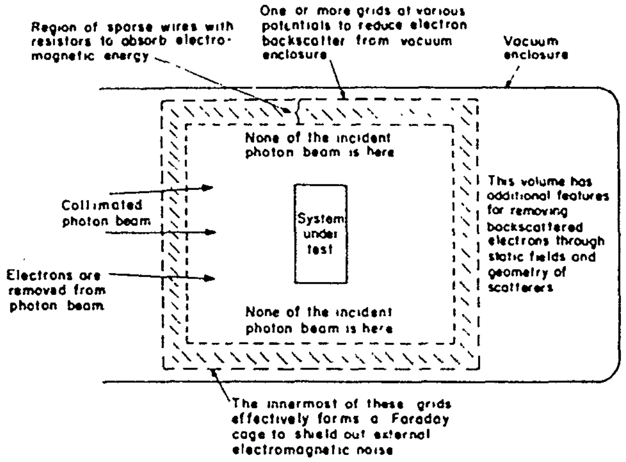


Fig. 19. Photons from flash X-ray machine driving an exoatmospheric system in test chamber with properties approximating free space.

The more general case shown in Fig. 19 requires control of the exterior electron and electromagnetic environment as well [95], [96], [103], [125], [126], [128], [129], [135], [138]. These are in addition to the vacuum, geomagnetic field, and incident photons to be controlled. This can be accomplished to some degree by constructing an electron trapping grid near and biased negative with respect to the vacuum chamber wall; the test object is biased at approximately the same potential as this grid. In order to damp the cavity resonances or reflections of the fields from this grid, a sparse grid of resistors or more elaborate impedance elements is distributed inside and attached to the conducting electron trapping grid (which also serves as a shield against external noise from the photon pulser and electron motion in the outer region).

B. Electron Driven Simulators (Second Removed Simulation)

If one replaces the incident photons by the resulting electrons (calculated and/or measured) emitted from the materials comprising the system, then one has a somewhat less complete simulation. One can place electron emitters on the system to approximate the electron emission from each section of the system surfaces. The previous discussion concerning the vacuum, electron trapping, and electromagnetic structures applies to this type of simulation as well.

C. Electric Dipoles Around the Test Object (Third Removed Simulation), DIES

If one assumes that the trajectories of the electrons emitted from the test object (including any nonlinear effects) are known (at least to a reasonable approximation), then one can attempt to reproduce the volume distribution of the resulting source current density by other means. If we consider some electrically small volume of space as illustrated in Fig. 20, the current density through that volume can be replaced by an electric dipole with moment p equal to the volume and time integral of the current density in the elementary volume. If this is repeated for every significant elementary volume, and

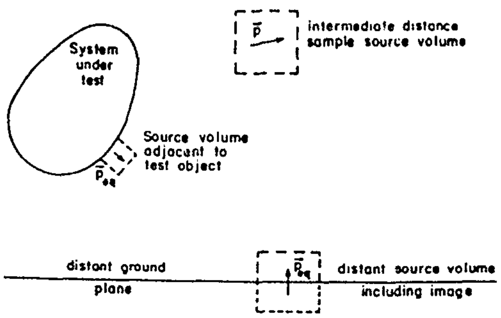


Fig. 20. Use of electric dipoles to replace source current density.

the resulting signals (such as voltage or current) at each position of interest in the test object are summed, then in principle the correct result is obtained. Note that the dipoles need not have the same waveform as the time integral of the current density, or can even be operated in a CW manner; Fourier transform techniques can correct the data. In converting from current density in a small volume to electric dipoles, there is the problem of the current crossing boundaries from one volume to the next; for adjacent volumes these effects cancel when the effects of the dipoles replacing the source currents are added. More significantly the elementary volumes at the farthest distances used in the simulation have an "outer boundary" error of this type. The elementary volumes adjacent to portions of the test object also have to have special dipoles connected to the test object to simulate the electrons leaving from and returning to the test object in each such elementary volume. Note that this technique does not in its basic form include changes induced in the impedances of the system under test, although some compensation can in principle be made for this.

In principle one can have all the dipoles operated in proper timed or phased sequence to obtain an experimental superposition. However, the dipoles in such a case would have to be made very small in physical dimensions to avoid significant mutual interaction and significant alteration of the response properties of the test object. Note also that the elementary volumes near the test object must be smaller in characteristic dimensions than the local dimensions of interest on the test object. For distant elementary volumes one can avoid effects of reflections from the earth by making a dipole which uses its image in the earth by construction of a ground plane on the earth surface; proper orientation with respect to the test object is secured by rotating the test object. This general simulation concept is referred to as DIES (*di*pole *e*nvironment for *S*GEMP).

D. Magnetic Dipoles on the Test Object (Fourth Removed Simulation), PARTES

Carrying the SGEMP phenomenon a step further, one can consider the incident electric field on the test object due to the source currents in the space around and inside it. The appropriate incident electric field can be calculated by an integral over the source current density with the free-space dyadic Green's function. This incident field can be produced in an average sense over patches of the test object's surfaces by cutting slots in the surfaces across which a voltage is impressed. Alternatively, a magnetic dipole (loop) can be placed on such surfaces to produce what is sometimes referred to as a magnetic frill. Note that on opposite sides of a conducting surface opposite magnetic dipole moments are required if both sides are significant in the response (see Fig. 21).

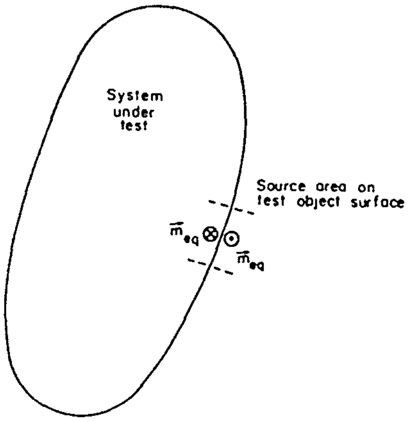


Fig. 21. Use of magnetic dipoles to replace incident electric field on test object.

In accounting for the electrons leaving the object, surface singularities occur in calculating the resultant incident field. The volume near the object can be accounted for, as in the case of third removed simulation, by electric dipole moments orthogonal to the test object surfaces. Note that this concept also applies to nonsource-region simulation as in Section II, except without the problem of the electrons leaving the object surface. This general concept is referred to as PARTES (*p*iece-wise *a*pplication of *r*adiation *t*hrough an *E*MP *s*imulator).

VI. SUMMARY

When designing a specific EMP simulator with some application in mind there are various points to be considered if one is to arrive at a somewhat optimum design, at least from an electromagnetic quality viewpoint. The following checklist, while not complete, will certainly help to organize EMP simulator selection and design.

1. Find the best type of EMP simulator.

a) What type of EMP is to be simulated?
b) Where is the system location?
c) Is more than one type of EMP simulator applicable?
d) What is the most efficient type of EMP simulator in terms of money, time, etc. for the same quality of the simulated EMP environment?
e) Are any auxiliary simulators needed for driving long appendages?

2. Determine all the major dimensions and other electromagnetic characteristics.

a) What are the dimensions of the systems to be tested?
b) What distortion of the system response is to be allowed (deviations of various parameters) associated with scattering of fields from the system to the simulator structure and back to the system etc. for various times

and various frequencies across the spectrum, as well as for incorrect impedances within the system?

c) What distortion of the fields, currents, etc. incident on the system is to be allowed due to nonideal characteristics of the simulator itself such as launcher angles, array sizes, reflections, finite plate widths, earth conductivity, etc.?

d) Are the various figures of merit from *b* and *c* compatible with each other and their impact on cost, time, etc.?

e) If there are large appendages which must go out of the simulator volume, then what pulsers and impedances are to be used to produce the same effects as the appendages in the appropriate nuclear EMP, and how will the appendage simulator(s) connect into the main simulator structure (if appropriate)?

3) Determine the desired characteristics of the appropriate electrical pulsers, photon pulsers, and/or CW generators.

a) How fast should the pulse rise?
b) What should the pulse amplitude be?
c) What should the pulse decay time be?
d) What low frequency content should the pulse have?
e) How smooth should the Fourier transform of the pulse be as a function of frequency over some frequency range?
f) Should there be more than one type of pulser (single shot, repetitive, different sizes)?
g) What should the pulser source impedance be?
h) How much power should a CW generator have?
i) Over what range of frequencies should a CW generator operate and in what mode (swept, stepped, etc.)?

Note that the idea is to quantify the numerous nonideal features of the types of EMP simulators of interest so that a set of figures of merit can be assigned to a given simulator design in the context of a particular system or group of systems to be tested. Until one quantifies these figures of merit he does not know very much about how good the simulation is.

Remember that EMP is many things. Many nonnuclear weapon techniques can be used to simulate a nuclear EMP. Some examples of various simulator types already exist and various system tests have been performed using these. Design principles exist for yet more types of simulators. Specific examples of some of these types are under design or nearing completion. There is still much detailed work to be done to refine the design details for the various simulator types, more in some cases than in others.

REFERENCES

Most of the references come from the Sensor and Simulation Notes (SSN) started by Dr. Ralph Partridge of LASL in 1964 to develop this technology. I am currently the editor of these related note series including the Interaction Notes (IN) references here. These are available from the authors, the Defense Documentation Center, Cameron Station, Alexandria, VA 22314, and the Editor, Dr. Carl E. Baum, Air Force Weapons Laboratory (NT), Kirtland AFB, NM 87117. In addition, there are various memo series (associated with various simulators and simulator types) including RES, SIEGE, TORUS, ALECS, ARES, ATLAS, ACHILLES, ATHAMAS, NAVES, Miscellaneous Simulator, SGEMP Simulation, and likely others to follow; these treat various detailed questions and designs.

[1] R. E. Partridge, "EMP testing facility," SSN 1, Feb. 1964.
[2] C. E. Baum, "Impedance and field distributions for parallel plate transmission line simulators," SSN 21, June 1966.
[3] —, "A transmission line EMP simulation technique for buried structures," SSN 22, June 1966.
[4] —, "Impedances and field distributions for symmetrical two wire and four wire transmission line simulators," SSN 27, Oct. 1966.
[5] —, "The conical transmission line as a wave launcher and terminator for a cylindrical transmission line," SSN 31, Jan. 1967.
[6] —, "A lens technique for transitioning waves between conical and cylindrical transmission lines," SSN 32, Jan. 1967.
[7] —, "A circular conical antenna simulator," SSN 36, Mar. 1967.
[8] —, "The brewster angle wave matcher," SSN 37, Mar. 1967.
[9] —, "The capacitor driven, open circuited buried-transmission-line simulator," SSN 44, June 1967.
[10] —, "The single-conductor, planar, uniform surface transmission line, driven from one end," SSN 46, July 1967.
[11] —, "The diffraction of an electromagnetic plane wave at a bend in a perfectly conducting planar sheet," SSN 47, Aug. 1967.
[12] —, "The planar, uniform surface transmission line driven from a sheet source," SSN 48, Aug. 1967.
[13] —, "The buried-transmission-line simulator driven by multiple capacitive sources," SSN 49, Aug. 1967.
[14] R. W. Latham and K. S. H. Lee, "The buried transmission line simulator with an inductive energy source," SSN 50, Apr. 1968.
[15] T. L. Brown and K. D. Granzow, "A parameter study of two parallel plate transmission line simulators of EMP Sensor and Simulation Note 21," SSN 52, Apr. 1968.
[16] C. E. Baum, "Admittance sheets for terminating high-frequency transmission lines," SSN 53, Apr. 1968.
[17] G. W. Carlisle, "Matching the impedance of multiple transitions to a parallel-plate transmission line," SSN 54, Apr. 1968.
[18] R. W. Latham, "Interaction between a cylindrical test body and a parallel plate simulator," SSN 55, May 1968.
[19] C. E. Baum, "A distributed inductor for use with a two-dimensional simulator structure," SSN 57, June 1968.
[20] G. W. Carlisle, "Positioning of rods for uniform TEM waves," SSN 58, July 1968.
[21] R. W. Latham and K. S. H. Lee, "Waveforms on a surface transmission line with an inductive load," SSN 60, Aug. 1968.
[22] T. L. Brown, "A parameter study of open-circuited and short-circuited transmission line simulation for buried structures of EMP Sensor and Simulation Note 22," SSN 62, Sept. 1968.
[23] A. D. Varvatsis, "End correction for a buried transmission-line simulator," SSN 63, Sept. 1968.
[24] C. E. Baum, "A scaling technique for the design of idealized electromagnetic lenses," SSN 64, Aug. 1968.
[25] —, "Some limiting low-frequency characteristics of a pulse-radiating antenna," SSN 65, Oct. 1968.
[26] —, "A simplified two-dimensional model for the fields above the distributed-source surface transmission line," SSN 66, Dec. 1968.
[27] R. W. Latham and K. S. H. Lee, "Inductance of periodic distributed inductors," SSN 67, Jan. 1969.
[28] —, "Termination of two parallel semi-infinite plates by a matched admittance sheet," SSN 68, Jan. 1969.
[29] C. E. Baum, "Design of a pulse-radiating dipole antenna as related to high-frequency and low-frequency limits," SSN 69, Jan. 1969.
[30] D. E. Merewether, "Transient pulse transmission using impedance loaded cylindrical antennas," SSN 70, Feb. 1968.
[31] —, "Transient electromagnetic fields near a cylindrical antenna multiply-loaded with lumped resistors," SSN 71, Aug. 1968.
[32] C. E. Baum, "An equivalent-charge method for defining geometries of dipole antennas," SSN 72, Jan. 1969.
[33] R. W. Latham and K. S. H. Lee, "Pulse radiation and synthesis by an infinite cylindrical antenna," SSN 73, Feb. 1969. *See also:* —, "Transient properties of an infinite cylindrical antenna," *Radio Sci.*, vol. 5, pp. 715–723, Apr. 1970.
[34] M. G. Roberts and K. D. Granzow, "A model for transient reflections from objects within an above-ground simulator," SSN 75, Mar. 1969.
[35] D. W. Milligan, "The buried transmission-line simulator driven

by multiple capacitive sources and an inductive source," SSN 76, Mar. 1979.

[36] G. W. Carlisle, "Waveforms on a lossy non-uniform surface transmission line," SSN 77, Mar. 1969.

[37] J. P. Martinez and K. D. Granzow, "Three- and four-branch RLC network energy sources for the buried transmission line EMP simulator," SSN 79, Feb. 1969.

[38] C. E. Baum, "Resistively loaded radiating dipole based on a transmission-line model for the antenna," SSN 81, Apr. 1969.

[39] —, "Some considerations concerning a horizontally polarized transmission-line simulator," SSN 82, Apr. 1969.

[40] R. W. Latham and K. S. H. Lee, "Radiation of an infinite cylindrical antenna with uniform resistive loading," SSN 83, Apr. 1969.

[41] C. E. Baum, "The distributed source for launching spherical waves," SSN 84, May 1969.

[42] R. W. Latham, K. S. H. Lee, and G. W. Carlisle, "Division of a two-plate line into sections with equal impedance," SSN 85, July 1969.

[43] C. E. Baum, "A distributed-source conducting-medium simulator for structures near and below the ground surface," SSN 87, July 1969.

[44] R. W. Latham and K. S. H. Lee, "Waveforms near a cylindrical antenna," SSN 89, June 1969.

[45] G. W. Carlisle, "Impedance and fields of two parallel plates of unequal breadths," SSN 90, July 1969.

[46] C. E. Baum, "A parametric study of the uniform surface transmission line driven by a step function voltage and terminated in its high-frequency characteristic impedance," SSN 92, Aug. 1969.

[47] R. W. Latham, K. S. H. Lee, and R. W. Sassman, "Minimization of current distortions on a cylindrical post piercing a parallel-plate waveguide," SSN 93, Sept. 1969.

[48] C. E. Baum, "Some considerations concerning a simulator with the geometry of a half toroid joined to a ground or water surface," SSN 94, Nov. 1969.

[49] —, "A sloped admittance sheet plus coplanar conducting flanges as a matched termination of a two-dimensional parallel-plate transmission line," SSN 95, Dec. 1969.

[50] W. E. Page, and D. H. Peterson, "A numerical method for computing the propagation of an electromagnetic pulse guided over a material interface," SSN 96, Jan. 1970.

[51] C. E. Baum, "Some considerations concerning a simulator with the geometry of a cylinder parallel to and close to a ground or water surface," SSN 97, Jan. 1970.

[52] C. D. Taylor, G. A. Steigerwald, "On the pulse excitation of a cylinder in a parallel plate waveguide," SSN 99, Mar. 1970.

[53] C. E. Baum, "Some characteristics of planar distributed sources for radiating transient pulses," SSN 100, Mar. 1970.

[54] L. Marin, "Radiation from a resistive tubular antenna excited by a step voltage," SSN 101, Mar. 1970. *See also* —, "Transient radiation from a resistive, tubular antenna," *Radio Sci.*, vol. 9, pp. 631-638, June 1974.

[55]. D. L. Wright, "Sloped parallel resistive rod terminations for two-dimensional parallel-plate transmission lines," SSN 103, May 1970.

[56] C. D. Taylor, and T. H. Shumpert, "Electromagnetic pulse generation by an impedance loaded dipole antenna," SSN 104, Nov. 1968.

[57] T. H. Shumpert, "Some theoretical-numerical procedures for the study of the impedance loaded dipole antenna," SSN 105, Aug. 1969.

[58] C. E. Baum, "Distributed sources and terminations for launching and terminating plane waves either with or without a reflected plane wave," SSN 108, May 1970.

[59] P. R. Barnes, "Pulse radiation by an infinitely long, perfectly conducting, cylindrical antenna in free space excited by a finite cylindrical distributed source specified by the tangential electric field associated with a biconical antenna," SSN 110, July 1970.

[60] R. W. Latham and K. S. H. Lee, "Electromagnetic interaction between a cylindrical post and a two-parallel plate simulator, I," SSN 111, July 1970.

[61] C. E. Baum, "Low-frequency magnetic field distribution for a simulator with the geometry of a half toroid joined to the surface of a medium with infinite conductivity," SSN 112, July 1970.

[62] M. I. Sancer and A. D. Varvatsis, "Scattering of a plane electromagnetic wave by a screen with a sinusoidal conducting direction," SSN 114, Aug. 1970.

[63] L. Marin, "Effect of replacing one conducting plate of a parallel-plate transmission line by a grid of rods," SSN 118, Oct. 1970. *See also* —, "A grid of uniformly spaced rods parallel to a plate or between and parallel to two parallel plates," *IEEE Trans. Electromagn. Compat.*, vol. EMC-18, pp. 21-27, Feb. 1976.

[64] —, "Waveforms on a nonuniform surface transmission line with an RC-load," SSN 119, Oct. 1970.

[65] A. D. Varvatsis and M. I. Sancer, "Low-frequency magnetic field interaction of a half toroid simulator with a perfectly conducting hemisphere," SSN 120, Oct. 1970.

[66] K. S. H. Lee, "Electromagnetic interaction between a cylindrical post and a two-parallel-plate simulator, II (a circular hole in the top plate)," SSN 121, Nov. 1970.

[67] A. D. Varvatsis and M. I. Sancer, "Low-frequency magnetic field distribution of a half toroid simulator joined to a finitely conducting ground: Simple ground connections," SSN 122, Feb. 1971.

[68] M. I. Sancer and A. D. Varvatsis, "Low-frequency magnetic field distribution of a half toroid simulator joined to a finitely conducting ground: modified ground connections," SSN 123, Feb. 1971.

[69] R. W. Latham and K. S. H. Lee, "Magnetic field on a cylinder in a loop," SSN 124, Feb. 1971.

[70] C. E. Baum, "Some characteristics of electric and magnetic dipole antennas for radiating transient pulses," SSN 125, Jan. 1971.

[71] D. F. Higgins, "The diffraction of an electromagnetic plane wave by interior and exterior bends in a perfectly conducting sheet," SSN 128, Jan. 1971.

[72] M. I. Sancer and A. D. Varvatsis, "Geometrical diffraction solution for the high frequency-early time behavior of the field radiated by an infinite cylindrical antenna with a biconical feed," SSN 129, May 1971.

[73] A. D. Varvatsis and M. I. Sancer, "Low-frequency magnetic field interaction of a half toroid simulator with a perfectly conducting half prolate spheroid," SSN 131, June 1971.

[74] T. B. A. Senior, "The diffraction matrix for a discontinuity in curvature," SSN 132, June 1971.

[75] L. Marin, "A cylindrical post above a perfectly conducting plate, I (static case)," SSN 134, July 1971.

[76] F. M. Tesche, "On the behavior of thin-wire scatterers and antennas arbitrarily located within a parallel plate region, I (the formulation)," SSN 135, Aug. 1971. *See also* "On the behavior of thin-wire antennas and scatterers arbitrarily located within a parallel-plate region," *IEEE Trans. Antennas Propagat.*, vol. AP-20, pp. 482-486, July 1972.

[77] L. Marin, "A cylindrical post above a perfectly conducting plate, II (dynamic case)," SSN 136, Aug. 1971.

[78] S. K. Cho, C-M. Chu and C-T, Tai, "Proximity effect of semi-infinite parallel plate transmission line in the presence of a perfectly conducting ground," SSN 137, Aug. 1971.

[79] M. I. Sancer and A. D. Varvatsis, "A comparison of the high frequency-early time behavior of the fields radiated by a capped and uncapped biconical antenna," SSN 138, Oct. 1971.

[80] K. S. H. Lee, "A vertical post inside a two-parallel-plate simulator," SSN 139, Oct. 1971.

[81] A. D. Varvatsis and M. I. Sancer, "Electromagnetic interaction between a perfectly conducting sphere and a two-parallel-plate simulator, I (top plate removed)," SSN 140, Oct. 1971.

[82] F. M. Tesche, "Numerical determination of the step wave response of a thin-wire scattering element arbitrarily located above a perfectly conducting ground plane," SSN 141, Feb. 1972 *See also* "Transient response of a thin-wire antenna or scatterer near a conducting ground plane," *IEEE Trans. Antennas Propagat.*, vol. AP-22, pp. 352-355, Mar. 1974.

[83] D. F. Higgins, "The effects of constructing a conical antenna above a ground plane out of a number of thin wires," SSN 142, Jan. 1972.

[84] C. E. Baum, "General principles for the design of ATLAS I and II, Part I: ATLAS: Electromagnetic design considerations for horizontal version," SSN 143, Jan. 1972.

[85] —, "General principles for the design of ATLAS I and II, Part II: ATLAS: Electromagnetic design considerations for vertical version," SSN 144, Jan. 1972.

[86] —, "General principles for the design of ATLAS I and II,

Part III: Additional considerations for the design of the terminations," SSN 145, Mar. 1972.

[87] —, "General principles for the design of ATLAS I and II, Part IV: Additional considerations for the design of pulser arrays," SSN 146, Mar. 1972.

[88] T. B. A. Senior and G. A. Desjardins, "Modified biconical antennas," SSN 147, Mar. 1972.

[89] C. E. Baum, "General principles for the design of ATLAS I and II, Part V: Some approximate figures of merit for comparing the waveforms launched by imperfect pulser arrays onto TEM transmission lines," SSN 148, May 1972.

[90] D. F. Higgins, "A method of calculating impedance and field distribution of a multi-wire parallel plate transmission line above a perfectly conducting ground," SSN 150, Feb. 1972.

[91] C. E. Baum, "EMP simulators for various types of nuclear EMP environments: An interim categorization," SSN 151, July 1972.

[92] C. E. Baum, *et al.* "Electromagnetic design calculations for ATLAS I, design 1," SSN 153, June 1972.

[93] T. K. Liu, "Direct time domain analysis of linear EMP radiators," SSN 154, July 1972.

[94] D. F. Higgins, "The effect of a perfectly conducting ground plane with a symmetrically located semi-cylindrical hump on the impedance and field distribution of a two-wire transmission line," SSN 155, June 1972.

[95] C. E. Baum, "A technique for simulating the system generated electromagnetic pulse resulting from an exoatmospheric nuclear weapons radiation environment," SSN 156, Sept. 1972.

[96] T. H. Shumpert, "Capacitance calculations for satellites, Part I, Isolated capacitances of ellipsoidal shapes with comparisons to some other simple bodies," SSN 157, Sept. 1972.

[97] M. I. Sancer and A. D. Varvatsis, "The effect of flanges on the inductance of a sloped termination for a parallel-plate simulator," SSN 158, Nov. 1972.

[98] Z. L. Pine and F. M. Tesche, "Pulse radiation by an infinite cylindrical antenna with a source gap with a uniform field," SSN 159, Oct. 1972. *See also* —. "Calculation of the early time radiated electric field from a linear antenna with a finite source gap," *IEEE Trans. Antennas Propagat.*, vol. AP-21, pp. 740-743, Sept. 1973.

[99] C. E. Baum and H. Chang, "Fields at the center of a full circular TORUS and a vertically oriented TORUS on a perfectly conducting earth," SSN 160, Dec. 1972.

[100] C-M. Chu and S. K. Cho, "Field distribution for parallel plate transmission line of finite width in proximity to a conducting plane," SSN 161, Nov. 1972.

[101] M. I. Sancer and A. D. Varvatsis, "The reduction of wasted energy delivered outside of a parallel-plate simulator fed by a sloped source array," SSN 162, Jan. 1973.

[102] A. D. Varvatsis and M. I. Sancer, "Performance of an admittance sheet plus coplanar flanges as a matched termination of a two-dimensional parallel-plate transmission line, I. perpendicular case," SSN 163, Jan. 1973.

[103] F. M. Tesche, "Study of a charged wire grid for reducing electron backscatter in EMP satellite simulators," SSN 164, Dec. 1972.

[104] C. E. Baum and D. F. Higgins, "Electromagnetic design calculations for ATLAS II, Design 1," SSN 165, Jan. 1973.

[105] R. W. Latham, "The effective radii approximation for the capacitance of a body within an enclosure," SSN 166, Jan. 1973.

[106] T. K. Liu, "Space-time domain magnetic field integral equation in the solution of an infinite cylindrical antenna with a biconical feed," SSN 167, Nov. 1972.

[107] T. C. Mo, C. H. Papas, and C. E. Baum, "Differential geometry scaling method for electromagnetic field and its applications to coaxial waveguide junctions," SSN 169, Mar. 1973. *See also* —, "General scaling method for electromagnetic fields with application to a matching problem," *J. Math. Phys.*, vol. 14, pp. 479-483, Apr. 1973.

[108] T. K. Liu, "Impedances and field distribution of curved parallel-plate transmission-line simulators," SSN 170, Feb. 1973.

[109] M. I. Sancer and A. D. Varvatsis, "Capacitance bounds for geometrics corresponding to an advanced simulator design," SSN 171, Mar 1973.

[110] W. E. Page and T. L. Brown, "Pulse propagation in a ground transmission line EMP simulator," SSN 172, Mar. 1973.

[111] L. Marin, "Transient electromagnetic properties of two parallel wires," SSN 173, Mar. 1973.

[112] S. K. Cho and C-M. Chu, "A parametric study of a circular cylinder within two parallel plates of finite width," SSN 174, Jan. 1973.

[113] F. M. Tesche and Z. L. Pine, "Approximation to a biconical source feed on linear EMP simulators by using N discrete voltage gaps," SSN 175, May 1973.

[114] L. Marin, "Natural modes of two collinear cylinders," SSN 176, May 1973.

[115] F. M. Tesche, "Application of the singularity expansion method to the analysis of impedance loaded linear antennas," SSN 177, May 1973. See also —, "The far-field response of a step-excited linear antenna using SEM," *IEEE Trans. Antennas Propagat.*, vol. AP-23, pp. 834-838, Nov. 1975.

[116] Y-P. Liu, D. L. Sengupta and C-T. Tai, "On the transient waveforms radiated by a resistively loaded linear antenna," SSN 178, Feb. 1973. See also Y-P. Liu and D. L. Sengupta, "Transient radiation from a linear antenna with nonreflecting resistive loading," *IEEE Trans. Antennas Propagat.*, vol. AP-22, pp. 212-220, Mar. 1974, and D. L. Sengupta and Y-P. Liu, "Analytical investigation of waveforms radiated by a resistively loaded linear antenna excited by a Gaussian pulse," *Radio Sci.*, vol. 9, pp. 621-630, June 1974.

[117] C. E. Baum, "Singularity expansion of electromagnetic fields and potentials radiated from antennas or scattered from objects in free space," SSN 179, May 1973.

[118] R. W. Latham, "Reflection from an array of dielectric posts," SSN 180, June 1973.

[119] H. Chang, "Electromagnetic fields near the center of TORUS, Part 1: fields on the plane of TORUS," SSN 181, Aug. 1973.

[120] T. H. Shumpert, "EMP interaction with a thin-cylinder above a ground plane using the singularity expansion method," SSN 182, June 1973. See also K. R. Umashankar, T. H. Shumpert, and D. R. Wilton, "Scattering by a thin wire parallel to a ground plane using the singularity expansion method," *IEEE Trans. Antennas Propagat.*, vol. AP-23, pp. 178-184, Mar. 1975.

[121] C. E. Baum, "Early time performance at large distances of periodic planar arrays of planar bicones with sources triggered in a plane-wave sequence," SSN 184, Aug. 1973.

[122] D. L. Wright and J. F. Prewitt, "Transmission line model of radiating dipole with special form of impedance loading," SSN 185, Sept. 1973. See also D. L. Wright and J. F. Prewitt, "Radiating dipole antenna with tapered impedance loading," *IEEE Trans. Antennas Propagat.*, vol. AP-23, pp. 811-814, Nov. 1975.

[123] T. K. Liu, "Admittances and fields of a planar array with sources excited in a plane wave sequence," SSN 186, Oct. 1973.

[124] R. W. Latham, "Parameter study of reflection reduction by impedance grids," SSN 189, Feb. 1974.

[125] C. L. Longmire, "Considerations in SGEMP simulation," SSN 194, May 1974.

[126] M. A. Messier, "The effect of a center conductor on the resonant modes of a spherical cavity with a perfectly conducting wall," SSN 195, May 1974.

[127] M. A. Messier and C. L. Longmire, "The dampling of tank oscillations with conducting dielectric shells," SSN 196, May 1974.

[128] D. F. Higgins and C. L. Longmire, "Cavity mode excitation," SSN 197, May 1974.

[129] D. F. Higgins, "Backscatter control grid design study: Electromagnetic considerations," SSN 198, Mar. 1974.

[130] D. E. Merewether and C. Foster, "Numerical studies of volume dampers for system generated electromagnetic pulse (SGEMP) simulation chambers," SSN 199, May 1974.

[131] A. D. Varvatsis and M. I. Sancer, "Performance of an admittance sheet plus coplanar flanges as a matched termination of a two-dimensional parallel-plate transmission line, II. sloped admittance sheet," SSN 200, June 1974.

[132] L. Marin, "Modes on a finite-width, parallel-plate simulator, I. Narrow plates," SSN 201, Sept. 1974.

[133] K. K. Chan, L. B. Felsen, S. T. Peng, and J. Shmoys, "Diffraction of the pulsed field from an arbitrarily oriented electric or magnetic dipole by a wedge," SSN 202, Oct. 1973.

[134] G. Franceschetti, C. H. Papas, "Pulsed antennas," SSN 203,

Dec. 1973. See also —, "Pulsed antennas," *IEEE Trans. Antennas Propagat.*, vol. AP-22, pp. 651-661, Sept. 1974.

[135] T. L. Brown, "Spherical cavity resonant damping through the use of an impedance loaded shell inside the chamber," SSN 204, July 1974.

[136] E. F. Vance, "Direct voltage and current injection," SSN 205, Sept. 1974.

[137] C-M. Chu, "Mathematics of guided wave propagation in open structures," SSN 206, May 1974.

[138] S. H. Gurbaxani and D. E. Jones, "Analysis of periodic structures for trapping electrons in EMP simulators," SSN 207, Jan. 1975.

[139] T. Itoh and R. Mittra, "Analysis of modes in a finite width parallel-plate waveguide," SSN 208, Jan. 1975.

[140] K. M. Soo Hoo, "Numerical analysis of a transmission line EMP simulator," SSN 209, Jan. 1974. See also —, "Numerical analysis of a transmission line EMP simulator," IEEE Trans. *Electromagn. Compat.*, *vol.* EMC-17, pp. 85-92, May 1975.

[141] R. F. Blackburn and C. D. Taylor, "On the electromagnetic fields from a hybrid type of EMP simulator," SSN 211, Nov. 1975.

[142] C. E. Baum, "Interaction of electromagnetic fields with an object which has an electromagnetic symmetry plane," IN 63, Mar. 1971.

[143] —, "Electromagnetic pulse interaction close to nuclear bursts and associated EMP environment specification," IN 76, July 1971.

[144] F.M. Tesche, M. A. Morgan, B. Fishbine and E. R. Parkinson, "Internal interaction analysis: Topological concepts and needed improvements," IN 248, July 1975.

[145] C. E. Baum, "How to think about EMP interaction," in *Proc. 1974 Spring FULMEN Meeting.*

[146] T. T. Wu and R. W. P. King , "The cylindrical antenna with nonreflecting resistive loading," *IEEE Trans. Antennas Propagat.*, AP-13, pp. 369-373, May 1965.

[147] L. C. Shen and R. W. P. King, "The cylindrical antenna with nonreflecting resistive loading," *IEEE Trans. Antennas Propagat.*, AP-13, p. 998, Nov. 1975.

[148] W. R. Smythe, *Static and Dynamic Electricity*, 2nd ed., New York: McGraw-Hill, 1950.