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Sensor and Simulation Notes
Note 151

13 July 1972

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

Carl E. Baum
Air Force Weapons Laboratory

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, and on 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 non nuclear types of energy sources for the simulators. These include electrical 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. The present categorization is necessarily an interim one since the present concepts will undoubtedly be further refined and new categories developed as time goes on.

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Foreword

For about eight years now I have been designing EMP simulators for various types of EMP environments. Over the years patterns started to emerge among the various types of EMP simulators that I had considered. These patterns suggested where certain simulator types might be absent, and so in completing the patterns new EMP simulator types were developed. At the present time there are quite a few types of EMP simulators. As time goes on new types are developed and old ones are split up 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 as regards 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.

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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

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I. Introduction

The nuclear electromagnetic pulse (EMP) has been under investigation for some years now. The total range of problems considered under the heading of EMP is fairly broad beginning with the generation of the pulse and carrying through to the effects of the pulse on various electronic items in systems, including methods of protecting against it. The logical first area of concern is the description of the physics of the EMP generation and the resulting waveforms and amplitudes associated with the various electromagnetic quantities; this first area is often called either phenomenology or environment. A second area is that of sensors designed to measure various electromagnetic quantities associated with EMP including the environment and system response; also other types of instrumentation are associated with this measurement problem (and in some contexts detection problem). A third area is that of simulators designed to approximately reproduce various aspects of the nuclear EMP on systems of interest and thereby test them. A fourth area is that of the interaction of the electromagnetic fields, currents, etc. with systems of interest; this includes coupling of signals coming from the EMP environment through various stages until the signals arrive at positions in the system susceptible to upset or damage. A fifth area is that of the response of circuit components to various types of appropriate transient signals. A sixth area is that of techniques (often statistical) for the assessment of system vulnerability. Associated with some of these areas are techniques for reducing the susceptibility of the system to EMP at various stages of the transport of EMP into the system.

These technical areas form a convenient way to split up the various technical disciplines that are important to the overall EMP problem. However, as time goes on, these technical areas tend to further divide and new questions are asked. In some cases these areas overlap considerably. Such a case is the system generated EMP for which the system of interest itself (instead of external air) provides the high energy electron generation region for the nuclear weapon photons. In this case phenomenology (environment) and interaction become the same to a significant degree.

As one can see from this discussion EMP covers a rather broad range of topics. Considering the volume of the technical literature (the various note series in particular) a review of all EMP subjects would be large indeed. This note concentrates on one subject area, EMP simulation. As this note will illustrate, EMP simulation is itself a very large subject area.

First this note briefly describes (in section II) some of the major types of EMP environments so as to have some general description of what is being simulated. An important parameter of the environment is the location of the nuclear detonation with respect to the atmosphere and surface of the earth (or other celestial bodies not considered here). Thus one can mention airbursts, surface bursts, and high altitude bursts. Another very important parameter of the environment is the location of the system relative to the nuclear detonation position and the atmosphere and surface of the earth. A system (in the context of EMP) means any equipment of concern from the point of view of vulnerability to EMP. System particularly applies to some total set of physically interconnected equipment that responds as a whole to the EMP; it does not generally apply to "black boxes," equipment racks, or other similar types of subsystems. Examples of systems are missiles, aircraft, satellites, ships, land vehicles of various types, buildings, etc. In some cases it is somewhat problematical to define what is included in the system if it has long conducting appendages such as power and telephone lines; strictly speaking all such appendages should be included because they do affect the EMP response, but sometimes system is used to refer to only the localized collection of equipment. It is the combination of nuclear detonation position and system position with respect to the earth surface and atmosphere that determines the EMP environment at the system. A very important distinction in EMP environments depends on whether or not the system is in the nuclear source region where source currents, ionization, and associated nuclear radiation such as γ rays and X rays are present.

After considering some of the features of the EMP environment then some of the features of EMP simulators are discussed (in section III) so as to help categorize EMP simulators according to their basic electromagnetic characteristics. Then several distinctive EMP environment situations are chosen (sections IV through VII). For each of these types of EMP environments various types of EMP simulators are described. Some simulators are better than others for various tasks. The simulators vary in the quality of the electromagnetic environment produced, size, and complexity.

Some of the simulator concepts have been realized in existing hardware. Other concepts only exist on paper at present. Many of the simulator design concepts have been written up in the Sensor and Simulation Notes. The other design concepts for the most part are presently in my notebooks where some of them have been buried for quite some time. In this note then these concepts can be briefly described so as to better fill in the pattern of EMP simulators considered as a whole.

EMP simulators come in various sizes. This note concentrates on what might be referred to as EMP simulators proper or system level EMP simulators. Such simulators in their purest forms excite the entire system with an electromagnetic distribution which is nearly the same over the entire system as the nuclear EMP. On a smaller scale system level simulators can include those which drive only a portion of the exterior of the system (such as an antenna or an aperture) but with the remainder of the system electrically configured in its operational configuration. Not included in this note are those "simulators" used to test pieces of the system such as "black boxes," racks, etc. or to drive the system at some intermediate position on the coupling path from the system exterior to what are often referred to as "critical circuits."

As more thought is given to the EMP simulator question it is to be expected that more simulator concepts will evolve and new relations will be found among the various design concepts. Thus, as the title of this note suggests, the present description is not necessarily complete. The present categorization of EMP simulators is an interim one. The state of the art is evolving fairly rapidly.

II. Brief Survey of the General Types of EMP Environments

The basic physical processes leading to the generation of the nuclear electromagnetic pulse have been known for some time now. The high energy photons (γ rays and X rays) interact with air, soil, water, and materials associated with the system of interest to produce high energy electrons by Compton and photoelectric processes with energies up into the few MeV range. These photons may come from the nuclear weapon directly or after some scattering, or they may come from the interaction of neutrons with air, soil, etc. producing γ rays. At sea level the range of these electrons can be as much as a few meters in air; this increases as the reciprocal of the air density as the altitude is increased. Collectively these electrons represent a source current density (amps/meter^2) which is used as the source in Maxwell's equations when calculating the EMP for some burst geometry.

In generating these source current densities the γ rays are often more important than the X rays since the X rays have a much smaller mean free path than γ rays in typical materials such as air. The X rays then tend to be filtered out by air in some cases comparatively close to the detonation position so that out at distances of interest from the detonation the γ rays dominate the EMP production. However, this is not always the case. If one considers positions close enough to the detonation such that the X-ray attenuation is not very large, then the X rays can make an important contribution to the source current density. Furthermore for exoatmospheric detonation and system locations, assuming that the path between the two is also exoatmospheric, there is negligible X-ray attenuation and the X rays are then important for this case.

In the case of an EMP source region in air the high energy electrons ionize the air in the process of slowing down. A high energy electron produced from a γ-ray scatter may produce of the order of 10^4 electron-ion pairs. The low energy electrons so produced tend to dominate the air conductivity due to the electron mobility of the order of 1 m^2/(Vs) for sea level air. This mobility is a strong function of the electric field, however, making the problem nonlinear. The conduction electrons are lost through attachment and recombination processes with the air molecules and ions. The most important of these processes in typical cases is electron attachment to oxygen molecules with a time constant of about 10^{-8} s at sea level.

Considered in detail the various processes associated with the air conductivity are quite complex. Numerous types of ions are transiently present. In some cases such as in high altitude source regions the combination of large electric fields with low air densities leads to additional ionization associated with collisions of the energetic conduction electrons with air molecules. In other cases such as sufficiently close in to surface bursts (or air bursts) the ion densities can be large enough to affect the electron mobility through electron-ion collisions.

Air conductivity is not the only conductivity to be considered. Close in to surface bursts the soil conductivity and the conductivity of dielectrics associated with the system can be significantly altered by nuclear radiation and the large electromagnetic fields.

In some cases conductivity is not the appropriate way to view the movement of electrons by the electromagnetic fields present. For an exoatmospheric system exposed to γ and X rays from a nuclear weapon the high energy electrons knocked off the system materials into space or into the interior of the system can have their trajectories significantly altered by the electromagnetic fields generated by these same electrons. This is a nonlinear problem involving Maxwell's equations combined with equations of motion for the electrons. There are even cases in the atmosphere where the high energy electrons can have their trajectories significantly altered by the EMP fields. The static magnetic field of the earth can also significantly affect the motion of the high energy electrons; particularly at high altitudes this can provide a very significant source mechanism.

For approximately defining different types of nuclear EMP the concept of a source region is rather useful. In the atmosphere this term is used to denote that region of space dominated by source current density and associated conduction current density as compared to displacement current density. This has implications for understanding system interaction with EMP. To be outside the source region means that an electromagnetic wave is incident on the system from some detonation which is sufficiently far away that the electromagnetic characteristics of the media surrounding or within the system are not significantly altered by the nuclear radiation. This greatly simplifies the understanding of the EMP interaction in such a case. Not surprisingly, more detailed systems interaction work, both theoretical and experimental, has been done for this case.

Inside a source region in air the physical processes are considerably more complex. The air conductivity varies with time and is a function of the electric field so that the problem is nonlinear. Current density is then somewhat distinct from electric field for such a case; current density is then an important part of the environment description.[12] In addition to the conduction and displacement current densities there is also the source current density of high energy electrons in the immediate vicinity of the system, inside the system in some cases, and flowing into and out of the system. Thus the source region is more complex electromagnetically due to a time varying and nonlinear parameter (conductivity) and a source term (current density of high energy electrons).

Another type of source region is basically the system itself if the system is exposed to the weapon γ rays and X rays in an exoatmospheric environment. It is the presence of the system itself which allows the photons to generate high energy electrons there. This type of EMP phenomenon is thus often called the system generated EMP. The physical properties of this type of source region are somewhat different from those of a source region in air. Both types of source regions are physically complex.

In order to have some typical rough numbers for the EMP source region parameters consider the γ rays which have an energy flux per unit area roughly like (all units MKSA unless otherwise noted)

$$\phi_\gamma = f_\gamma U \frac{e^{-\frac{r}{r_\gamma}}}{4\pi r^2} \tag{2.1}$$

where r_γ is the gamma ray mean free path which is roughly 200 m in sea level air but infinite in free space. The distance from the detonation to the observation point is r. The energy released by the detonation is U; a 10^{16} J weapon (corresponding to about 2.4 megatons) can be used as an example. The fractional energy in γ rays is f_γ which may be taken as a few tenths of a percent typically. For X rays the fractional energy f_X would be more like .8. Times of the order of 10^{-8} s can be used to convert such energies, total numbers of particles, etc. to rough peak rates.

Choose $f_\gamma \simeq .002$, a time of 10^{-8} s, a γ-ray energy of 2 MeV, a 10^{16} J weapon, a 200 m γ-ray mean free path, and a distance of 1 km as an example case. This gives a ϕ_γ of roughly 10^{12} watts/m^2 or 3×10^{24} photons/(m^{2}s). The range of the high energy electrons is roughly 10^{-2} that of the γ-ray mean free path giving about 3×10^{22} electrons/(m^{2}s) or about 5×10^3 amps/m^2. Such is a rather significant source current density. Of course closer to the detonation it can be significantly larger; farther away it can still be significant. For exoatmospheric interaction of weapon photons with a system the X rays are quite significant since there are so many more of them. In such a case the X rays should be included for electron generation but the resulting electrons also have significantly lower energies.

The air conductivity for sea level air can also be related to $\dot{n}_\gamma$, the number of γ rays per unit area per unit time. Take the electron mobility as 0.3 $m^2/(Vs)$, allowing for the effect of the electric field in decreasing this mobility; take the electron attachment time as 10^{-8} seconds and assume equilibrium (or steady state gamma rate). The generation rate of conduction electrons is

$$S_e \simeq \frac{\dot{n}_\gamma}{r_\gamma} \frac{U_\gamma}{U_o} \tag{2.2}$$

where U_γ is the photon energy and U_o is the energy for making an electron-ion pair or about 30 eV. For our example then S_e is about 300 $\dot{n}_\gamma$ or about 10^{27} electrons/(m^3s). This given an equilibrium electron density of about 10^{17} electrons/m^3 with a conductivity of about .5 S/m. For sea level air we have the rough conductivity estimate as

$$\sigma \simeq 1.5 \times 10^{-25} \dot{n}_\gamma \tag{2.3}$$

The current of high energy electrons, often termed the Compton current density is given by

$$J_c \simeq -1.5 \times 10^{-21} \dot{n}_\gamma \tag{2.4}$$

indicating a negative current density away from the detonation. The ratio J_c/σ from equations 2.3 and 2.4 is independent of $\dot{n}_\gamma$ with a magnitude of about 10^4 volts/m. This is the saturation electric field which is characteristic of the source region. Actually the electric fields in a source region in sea level air can be somewhat larger than this, approaching 10^5 V/m or even larger. The rough estimates here neglect details of time dependence and various more complex physical processes. More detailed calculations have been performed, some using intricate computer programs.

If the reader wishes to delve into the intricacies of the physics involved or the analytical and numerical techniques used for EMP environment calculations other notes, particularly the series of Theoretical Notes, should be consulted. For present purposes this note only outlines the general physical processes and some of the magnitudes involved as background for considering the EMP simulation problem.

One general point to be made in this discussion, however, is that while the nuclear EMP can be thought of as encompassing a unified class of phenomena the detailed quantitative waveforms for the various important electromagnetic parameters vary considerably from case to case. This has a significant impact on EMP simulator design in that there are several kinds of EMP to be simulated depending on the relative positions of the nuclear detonation, system of interest, atmosphere, and ground (or water) surface defining the type of EMP of interest. In order to facilitate the discussion of EMP simulators then let us briefly look at several types of EMP.

A. Air burst

While an air burst is not the most important detonation geometry from an EMP point of view it is one of the simpler cases to consider. As shown in figure 2.1 (not to scale) an air burst has a roughly spherically symmetric source region. As such it does not very efficiently produce electromagnetic fields outside of the source region. Thus the electromagnetic fields propagated to systems near the ground surface, in the air away from the source region, and exoatmospheric (including some propagation through the ionosphere) are not very significant from a system vulnerability point of view. Other types of nuclear burst geometries produce more significant fields outside of source regions. The source region is not perfectly spherically symmetric due to asymmetries in the weapon and the atmosphere. Thus some fields are produced outside the source region but are interesting mostly from a diagnostic viewpoint.

Inside the source region there are basically radial current density and electric field. The rough spherical symmetry makes the magnetic field (and associated voltage density) small compared to that in a surface burst source region. The time scale for the EMP is similar to that for a surface burst with rise times in the 10^{-8} s range and width in the 10 μs through 100 μs range. The electric field and current density amplitudes are as discussed previously. The pulse widths are associated with source region size and the time for the neutrons to interact with the air to produce more γ rays in the source region.

The source region size is somewhat dependent on the weapon yield. Using a criterion of $\sigma \simeq \omega\varepsilon_0$ with $\omega \simeq 10^8\ \mathrm{s}^{-1}$ for the early radiation peak gives a conductivity of $\sigma \simeq 10^{-3}$ S/m. For sea level air density this would imply $\dot{n}_\gamma \simeq .7 \times 10^{22}$ photons/$(\mathrm{m}^2\mathrm{s})$ and $J_c \simeq -10$ amps/m^2. For our example 10^{16} J weapon this gives a source region radius of roughly 2 km. This estimate applies to both surface bursts and air bursts except that as the altitude of the air burst is raised the source region radius increases due to the decreasing air density.

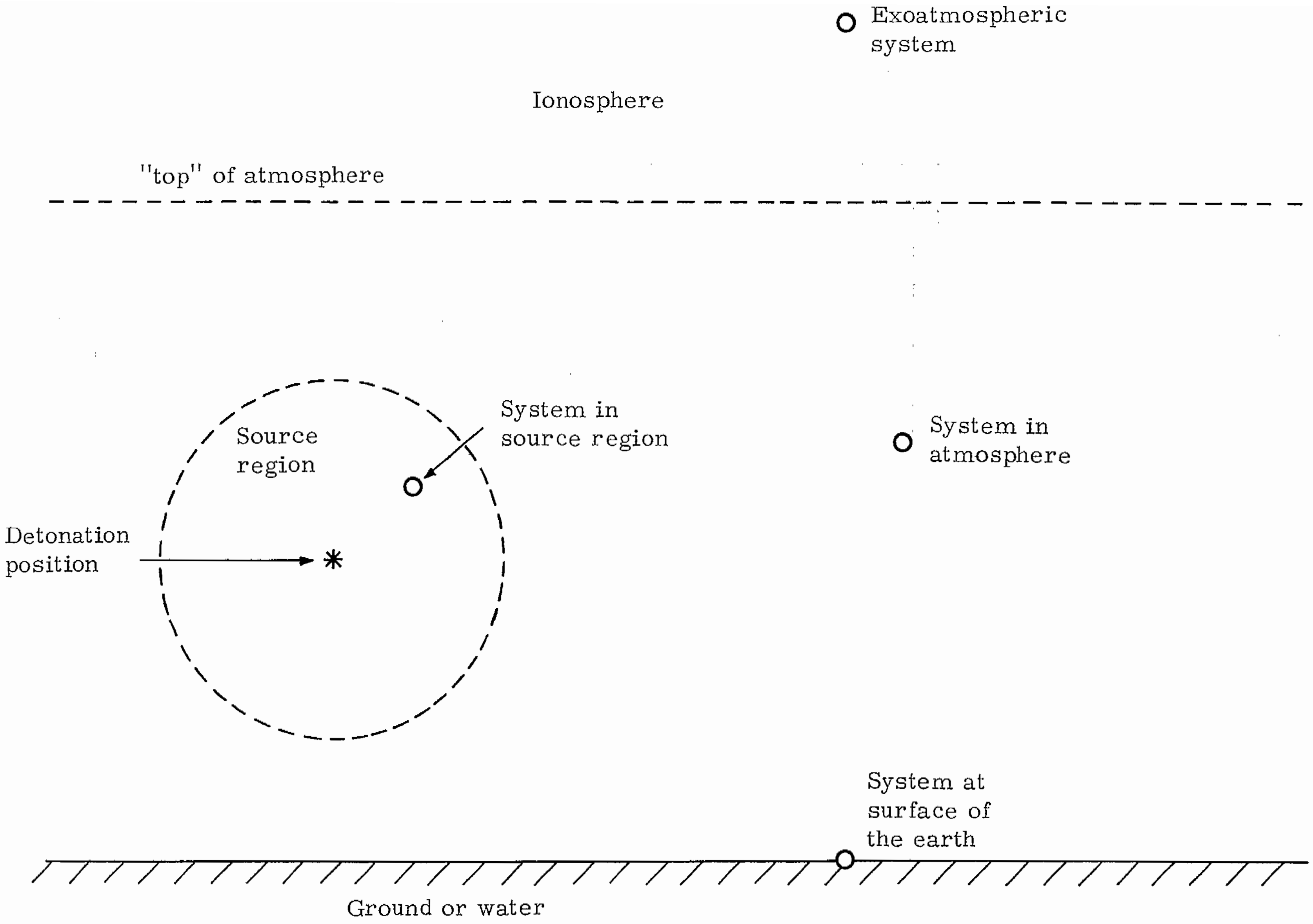


Figure 2.1 Air Burst Geometry

The definition of the source region radius as above is somewhat arbitrary. The air conductivity changes with time, decreasing after the peak along with the source current density. As one goes out in time, however, the most significant frequencies (or portion of the Fourier transform) also shift toward lower frequencies associated with these larger times. Other reasonable definitions could then be made which would give roughly similar radii to that discussed previously. Of course the source region does not have any well defined boundary since the source current density and air conductivity magnitudes vary smoothly with r. The photon source $\dot{n}_\gamma$ changes significantly over a mean free path. Thus some distance of the order of 200 m is one measure of the indefiniteness of the source region radius.

B. Surface burst

Figure 2.2 (again not to scale) shows a nuclear surface burst geometry for which the detonation point is near to the earth's surface but above it. In this case the nuclear source region contacts (and even penetrates into) the earth surface. As in the case of the air burst the system can be various places outside the source region. Electromagnetic fields can propagate to systems near the surface of the earth, in the atmosphere, and outside the atmosphere. Such fields away from the source region tend to be larger than for air bursts (except for some of the high frequency portions of the signal at some directions from the detonation). This is due to the large asymmetry associated with the presence of the earth surface giving a somewhat hemispherical source region.

Inside the source region the system might be located near the earth surface (including just below the surface) or up in the conducting air. A system near the earth surface is generally of greater interest since mechanically hardened sites tend to fall in this category. EMP simulators for such sites form an important class of such simulators.

The field amplitudes for the electric field and current density are similar to those for the air burst discussed previously. The electric field has a saturation amplitude in the 10^4 V/m range but can be significantly larger. For the example case considered before the source current density is of the order of 10 amps/m^2 peak near the edge of the source region of 2 km radius, but more like 10^4 amps/m^2 at 1 km from the detonation. The time scales are of the order of 10^{-8} s for the rise with pulse widths in the 10 μs to 100 μs range.

With the presence of the ground surface there is a significant magnetic field produced. Inside the source region diffusion depths (or skin depths) in the air and ground limit

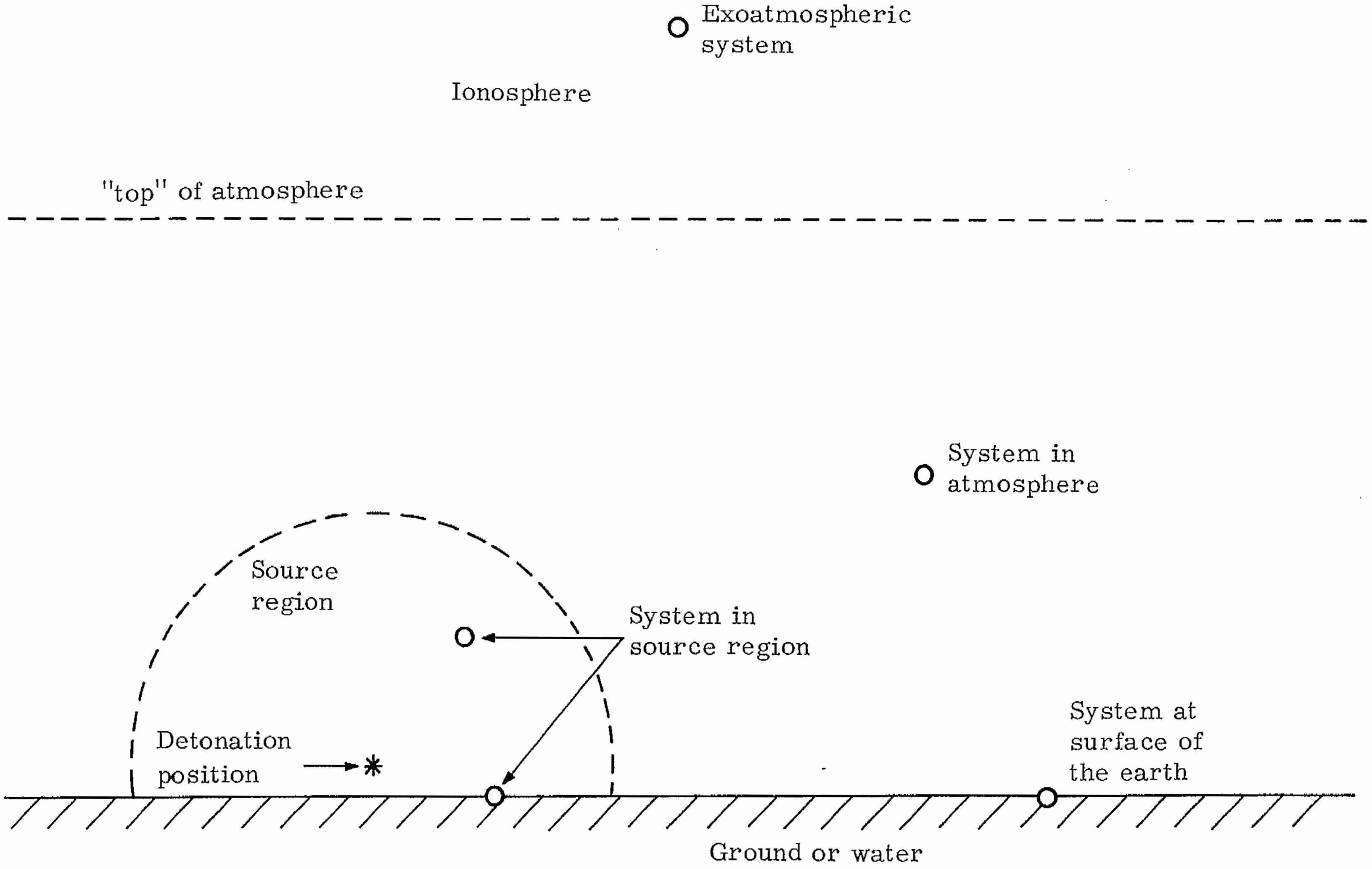


Figure 2.2 Surface Burst Geometry

the extent to which the ground surface can influence the fields at some position for various times. As an example let the ground be perfectly conducting and the relaxation time of the air ε_o/σ be small compared to 10^{-8} s. Then from a previous note we have[11]

$$H \simeq J_c c \frac{\varepsilon_o}{\sigma} 2 \sqrt{\frac{\tau}{\pi} \frac{\sigma}{\varepsilon_o}} \tag{2.5}$$

Letting $\tau \simeq 10^{-8}$ s and $\sigma \simeq .5$ corresponding to $r \simeq 1$ km for our example case gives $J_c \simeq -5 \times 10^3$ amps/m^2 and $H \simeq -7 \times 10^2$ amps/m which in terms of B is of the order of 1 mT. In this case the magnitude of the E/H ratio is significantly less than the free space impedance of $\sqrt{\mu_o/\varepsilon_o}$ or about 377 Ω. As one goes in even closer to the detonation position the magnitude of the magnetic field gets even larger going into tens and more of milliteslas.

C. High altitude burst

Figure 2.3 (not to scale) shows what is usually termed a high altitude burst. The detonation position is above most of the atmosphere at an altitude exceeding about 40 km. There is an EMP source region in the immediate vicinity of the detonation position and a source region somewhat continuous toward the earth from the detonation since the atmospheric density is not zero at such altitudes. However, the low atmospheric density at such high altitudes makes such source regions less significant. Of course in such "exoatmospheric" source regions the weapon X rays are present in copious quantities so as to significantly influence such sources.

The most significant high altitude source region lies in the altitude range of roughly 20 km to 40 km. Here the air density is large enough to significantly interact with the weapon γ rays. At about 20 km altitude the γ rays have been attenuated sufficiently that the source region boundary is reached; this is similar to the source region radius previously discussed for surface bursts and air bursts. In this source region the same general physical processes occur as in other source regions in air. However, the relative magnitudes of these processes shift somewhat due to the low air density in this high altitude source region. The electron attachment time to neutral oxygen molecules is increased as is the electron mobility. The combination of large electric fields with low air density leads to some ionization (or breakdown) associated with sufficiently high energy of the conduction electrons. Note that the low air density means a large γ-ray mean free path and thus a smaller production rate (per unit volume) of

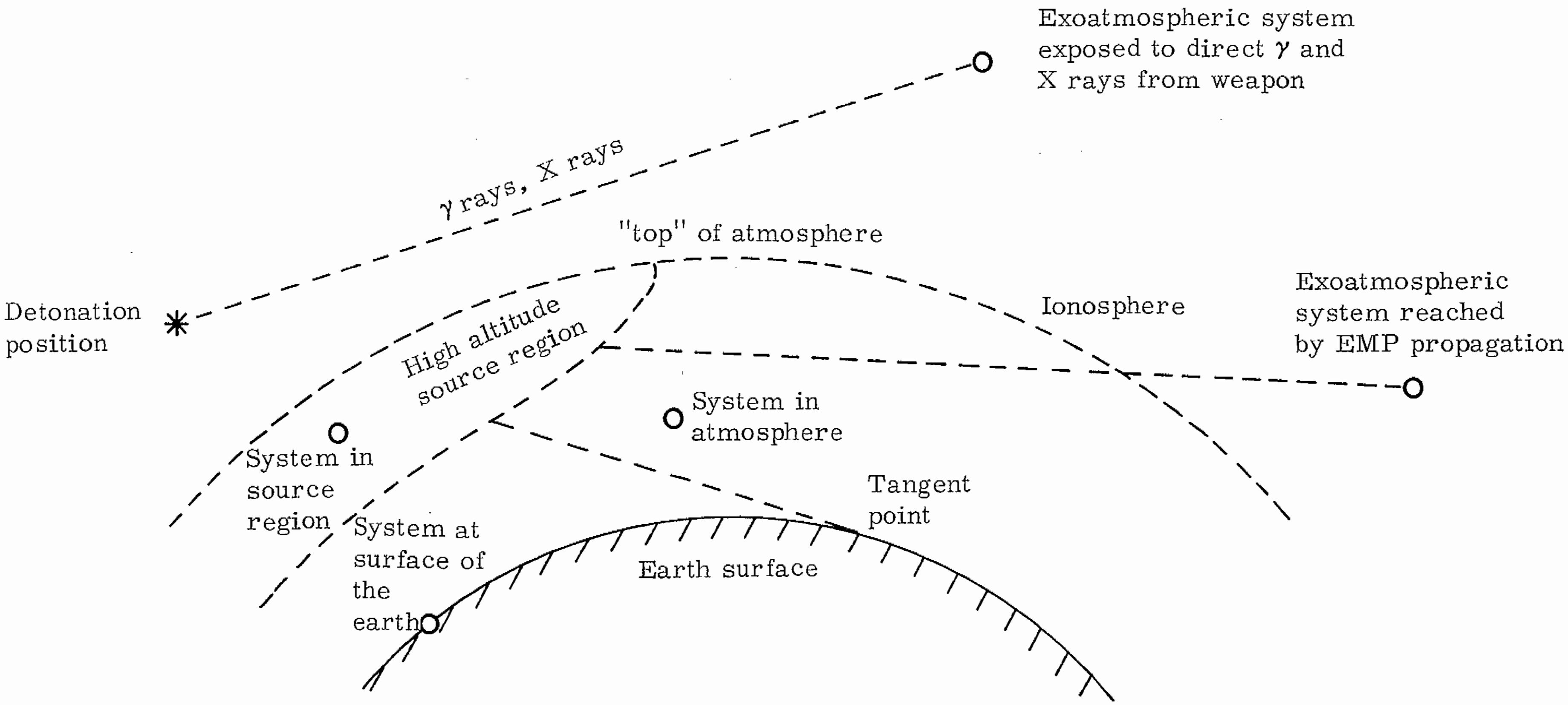


Figure 2.3 High Altitude Burst Geometry

conduction electrons S_e for a given rate of γ rays $\dot{n}_\gamma$ at a position of interest in the source region.

In changing some of these physical parameters in going from a surface burst to a high altitude burst the peak electric field amplitude stays about the same approaching 10^5 V/m. The time scales for the pulse are still in the 10^{-8} s range for the rise but in the μs range for pulse widths. The weapon neutrons come along much later because of the large distances from the detonation position to the source region so that the neutrons do not have much of an effect. This contrasts to a surface burst for which the neutrons are very important for increasing the EMP pulse width.

One very important physical process in the high altitude source region is the deflection of the high energy electrons by the earth's magnetic field present in the source region before the detonation. The high energy electrons have ranges of roughly 100 m or 1 km due to the small air density. The cyclotron radius of these electrons in the earth's magnetic field is of comparable magnitude. There is a radial source current density with average electron velocities parallel to the direction of γ-ray propagation. In addition, however, there is a source current density with direction perpendicular to the direction of γ-ray propagation and the magnitude of this transverse source current density is comparable to that of the radial source current density.

Inside this high altitude source region the EMP environment includes a separate current density besides the electric field. These complications of the electromagnetic parameters of the medium should be considered in designing EMP simulators for systems such as missiles which operate in this altitude range.

For the high altitude detonation it is important to consider system locations outside the high altitude source region where fields can propagate to the system from the source region. The large transverse source currents in the high altitude source region lead to a large radiated EMP with rise times in the 10^{-8} s range, peak electric fields approaching 10^5 V/m, and pulse widths in the μs range. The source region is rather large. It is limited basically by the curvature of the top of the earth's atmosphere, so that the weapon γ rays are roughly limited in a "line-of-sight" sense as to what portions of the top of the atmosphere they can illuminate. The field amplitudes fall off in a roughly r_o/r manner where r is the distance from the detonation to the observer and r_o is the distance along the same path from the detonation to the "bottom" of the source region.

There are various system locations illuminated by the EMP radiated by a high altitude source region that one can consider. First there is the case of the system in the atmosphere with no obstacles (such as the earth surface) to interfere with the EMP propagating directly toward the system. The ground reflection reaching the system is assumed to arrive much later in time than the initial signal so that their effects can be separated. This is a very important case, applying to missiles and aircraft in flight. Much work has been done in designing EMP simulators for this case. As shown in figure 2.3 an extension of this case is to exoatmospheric systems such as satellites which are not directly illuminated by γ rays and X rays from the detonation (due to atmospheric shielding) but are directly illuminated by the EMP from the high altitude source region. In this case the EMP may propagate through all or a portion of the ionosphere, dispersing the waveform considerably so that in the time domain it does not look much like the EMP incident on the ionosphere. One might also be concerned with airborne systems shadowed from the EMP by the earth surface. In such a case the wave diffracts around the earth and reflects off the ionosphere to reach the system with a distorted waveform.

Another important system location outside the source region is on or near the surface of the earth. With direct illumination of EMP from the source region there is a significant reflection from the surface of the earth in the vicinity of the system. An EMP simulator for such a case should include the ground reflection as an integral part of the EMP to be simulated. Numerous types of systems fall into this category and much work has been done to design EMP simulators for this case. Of course such systems can also be over the horizon so that they are reached by diffracted EMP with consequent waveform distortion.

There is another system location of interest for a high altitude detonation where the important source region is at the system itself due to the presence of the system. As shown in figure 2.3 the system is exoatmospheric (such as a satellite) and is directly illuminated by the weapon γ rays and X rays. The high energy electrons originate from the system materials and move both inside and outside the system. These high energy electrons are the source for what is termed the system generated EMP. The system interaction problem is quite different from that of a system illuminated by EMP away from a source region. Correspondingly EMP simulators for such a type of EMP should include the various additional effects.

III. Some General Characteristics of EMP Simulators

Before considering the many specific types of EMP simulators let us consider some of the general problems concerning EMP simulators. How is one type of EMP simulator distinguished from another? Can EMP simulators (at least some types) be divided up in a manner that one can consider certain features separately from others (at least approximately so)?

Note that principally system level EMP simulators are considered here. For the most part this means devices which apply electromagnetic fields, current densities, etc. over entire system geometries or at least major portions of systems in cases for which some large appendages (such as power lines, etc.) are not completely illuminated. Accounting for the effects of such appendages and including them in the simulator design is part of the overall EMP simulation problem.

In some cases only a portion of the total system is driven at one or more of its penetrations. In the context of the EMP phenomenon a penetration refers to some approximately localized part on the system exterior where electromagnetic energy can enter into the system interior relatively efficiently as compared to other portions of the system exterior. The concept of a penetration is useful for systems which can be approximately considered as having a bounding surface which divides outside from inside. Typical types of penetrations are apertures, deliberate antennas, power and signal cables where they connect into the "system surface," and other conductors such as pipes where they pass through this surface. Devices which drive such penetrations instead of the entire distributed system are also included as EMP simulators for our purposes.

There are many types of EMP simulators. One type of EMP simulator can be best distinguished from another type through their electromagnetic characteristics. A simulator is then categorized according to the distribution of electromagnetic fields, current density, etc. it is capable of producing in space and time (or frequency). The type of EMP simulator is not described, for example, by electromagnetic instrumentation (sensors etc.) used with the simulator, a test stand used to support a test item in the simulator without distorting the fields etc. produced by the simulator, or a specific item to be tested by the simulator. A simulator type is determined by the simulator itself and not other items associated with the simulator.

An EMP simulator can often be considered as comprising two important parts: an electromagnetic geometry and one or more electrical energy sources. By an electromagnetic geometry is meant a spatial distribution of conductors, insulators, lumped and distributed passive impedances, etc. which are used to form the spatial distributions of fields and related electromagnetic quantities. Source impedances can be significant in this regard in some cases. The role of the electromagnetic geometry is basically to establish some desired transfer function from the source(s) to the various spatial positions of interest for the electromagnetic quantities of interest. Depending on the simulator design this transfer function may be alterable in some desired manner by varying parameters of the simulator geometry so as to alter direction of wave incidence, polarization, etc. A given simulator·electromagnetic geometry can often be combined with various types of electrical energy sources to produce various temporal field distributions (waveforms) while still maintaining the same relations among the fields etc. in their Laplace transform (with respect to time) or frequency domain forms at the various positions of interest. Changing an electrical source corresponds in Laplace transforms to multiplying the Laplace transformed fields etc. by a function of the complex frequency which is the same function at all the positions of interest. For a single electrical source occupying a small region of space (compared to the significant parts of the electromagnetic geometry) the relative field values (in complex frequency form) produced at various spatial positions by the simulator are in general independent of the details of the electrical source as long as it is spatially sufficiently small.

There may be many electrical sources which are varied with respect to each other, such as with regard to turn on time to vary the spatial field characteristics. Then the source distribution in space and time (or frequency, at least in a relative sense among sources) is an important part of the simulator electromagnetic geometry.

A common type of electrical pulse generator is a capacitive source switched with some fast rise time into the simulator. For some simulator geometries this gives a fast rising and smoothly decaying waveform. However, other types of waveforms are achievable from other types of pulsers. Various impedance elements, dispersing networks, etc. can be combined with capacitive generators to alter the resulting waveforms. Other types of pulsers such as inductive energy sources can also be used.

A particular simulator electromagnetic geometry can be combined with various pulsers and in existing simulators this is often done. Examples are single-pulse high energy pulsers, lower energy repetitive pulsers, and continuous wave generators interchangeably connected onto one simulator. Considering this fact together with the transfer function of the simulator being independent of pulser type (although not independent of pulser distribution) then the most significant characteristic of an EMP simulator is its electromagnetic geometry. The pulser gives a scale factor to multiply times the electromagnetic distribution (in complex frequency domain).

In describing some type of EMP simulator then its electromagnetic characteristics are most important. These include the distribution of conductors, insulators, and various impedances in space as well as the actual resulting distribution of electromagnetic fields, currents, etc. It is on the basis of these quantities that EMP simulators can be divided into various types. Each type can have some descriptive name based on its distinctive electromagnetic geometry, its field distribution, or both. Such a name applies not just to one specific simulator but to the whole class of such EMP simulators, whether existing, under design, or just imagined. Examples of such descriptive names are transmission line, dipole, etc. In some cases acronyms are used to name various simulator types, such as RES, TORUS, SIEGE, etc. These are new words used to distinguish one type of simulator design (with perhaps several important design features) from another type of design. The set of design features is defined by one word or phrase constructed for the purpose. If such a word suggests features associated with the simulator it should suggest important features of the electromagnetic geometry and/or field distribution and of course be accurate in such suggestions.

An EMP simulator can also have a name to designate that specific simulator. As such it does not designate a type of EMP simulator but one particular simulator, simulator facility, simulator complex, etc. Such a name is similar to that of a person, place, etc. which names one person or thing and not a class. In choosing such names one can select names that are technically neutral. If, however, names of individual simulators are selected which are also technical terms, then the use of such terms should at least be technically accurate and refer to the basic electromagnetic characteristics of the simulator instead of various peripheral hardware associated with the EMP simulator. A name of a specific EMP simulator can also be an acronym such as ALECS, ARES, and ATLAS (ATLAS being under design while the others are operational); these simulators, as examples, are all members of a general class of EMP simulators, namely TEM transmission lines. These names all apply to specific EMP simulation facilities and not to classes of EMP simulators. For EMP simulation facilities with fixed location (not portable or transportable EMP simulators) such that they are not readily interchangeable with other nearly identical simulators by moving the replacement to the original site then a name for that individual facility is appropriate. A name for an individual simulator then is directly associated with the site on which the simulator is constructed. If the simulator at a given site is changed to a radically new design then the name can stay the same provided that if the name is an acronym the interpretation of the acronym is still applicable or can be modified to make it applicable.

One disadvantage of using technical terms (e.g. dipole) for names of individual simulators is that no distinction is made among the various specific simulators in that class so that it is more difficult to determine precisely which simulator is intended. However, in those cases where more than one simulator of nearly (if not exactly) the same design is built and is interchangeable they would best have the same designation. An example is RES I which designates a class of impedance loaded electric dipoles (which have been constructed in two different orientations for the electric dipole moment, horizontal and vertical). These simulators can be carried using flexible dielectric lines below large helicopters. The "I" indicates its general size in this case and other symbols (A, B, etc.) could be used to specify more details of the design and/or modifications in successive models. Similar types of designations can be given to high voltage pulse generators which can be used in more than one type of EMP simulator. A common type of such a generator is a capacitive generator driving a symmetrical circular bicone (or something approximating a bicone) which can be used with a RES type simulator structure as well as with a TORUS or some other types of hybrid EMP simulators.

This note considers various types of EMP simulators. One way to group these simulators is by their major applications to simulating certain types of EMP environments. The next four sections of this note each treat a group of EMP simulators principally intended for simulating the EMP environment associated with that section. Some simulators have one major application but can be also used as an experimental tool in simulating less completely other types of EMP environments. This division of EMP simulators is used to conveniently group the many simulator types. Also this division is a convenient one for the reader in that often the type of environment to be simulated is given and the problem is what kind of EMP simulator to use.

Simulators for four types of environments are considered. The first of these in section IV is for EMP environments outside of nuclear source regions. Such environments are simple compared to source region EMP environments. Much work has been done on EMP simulators for this important type of environment. The second type (section V) is that for nuclear source regions near the earth surface. The third type (section VI) is that for nuclear source regions in air (away from the earth surface). The fourth type (section VII) is that for the systems generated EMP in exoatmospheric regions where the system itself provides the source region.

The following four sections conveniently group EMP simulators according to their application. Such grouping, however, does not give the specific types of EMP simulators. As discussed previously EMP simulator categorization is based on the geometry of the important field forming parts of the structure (the electromagnetic geometry) and/or the characteristics of the resulting electromagnetic field distribution (the two being intimately related). Each of the following sections of this note then has various numbers of such simulator types. Each section is then a list of appropriate types of EMP simulators along with brief discussions of each. While one type can be applied in simulating more than one type of environment (with varying degrees of completeness) it is listed in the section corresponding to that environment for which it is most useful at present.

There are other ways to group the various types of EMP simulators, such as by looking for common features of the electromagnetic geometries and/or field distributions. One such method of grouping simulator types involves associating a number of spatial dimensions with the field distribution.

A zero dimensional or point simulator is one which produces fields, currents, etc. over a small volume (small dimensions compared to a wavelength) so as to couple electromagnetic energy in exciting the lowest order moments (usually dipole) of interest on the test object. As such a zero dimensional simulator is used for its static field distribution with the restriction that it is only the field, current density, etc. or some derivative of these quantities at one point which is of interest; the quantity or quantities of interest are made approximately uniform over the volume of interest (in the absence of the test object). Within these constraints different types of media and different components of incident fields are still possible. Various combinations of these quantities make zero dimensional simulators applicable to simulating different types of EMP environments on either a system level or for driving penetrations (apertures, antennas, etc.) leading into systems.

A one dimensional or line simulator can be used to drive a test object which can be idealized as confined near a path (line) which may be curved and have perhaps branches and closed loops. Such a simulator basically impresses an incident electric field tangential to the path from generators distributed near the path. The generators and associated impedances are connected together via conductors which are near but not on the path, and far enough away from the path so as to not greatly change the impedances associated with the currents on the system which lies approximately on the path. The system may be fairly large in its linear dimensions in several directions. However, given the thin wire approximation sufficient to confine most of the scattered field energy near the path then the simulator tries to approximately simulate a distributed incident wave by only driving near the path which is a one dimensional geometry even if not a straight line. Note that various media can be placed in the vicinity of the path to make the simulator more appropriate with respect to various EMP environments.

A two dimensional simulator is concerned with generating fields, current densities, etc. on surfaces. However, there are certain difficulties with respect to such a concept. For a volume without sources one need specify only tangential electric or magnetic fields on the surface of the volume to uniquely determine the fields in the volume. Such a simulator might then be considered three dimensional because quite complex (but not completely arbitrary) spatial field distributions can be produced in the volume. Thus such a third class can be termed two dimensional referring to the necessity of producing fields over a surface in order to obtain fields in a volume, or three dimensional referring to the three dimensional geometry of a large system which is illuminated over its entirety with some wavelengths small compared to the system size. Many EMP simulators are of this general type.

In some special cases one can try to distinguish between two and three dimensional EMP simulators. Suppose, for example, that the portion of the system exposed to EMP were basically a conducting surface with various penetrations. Further suppose that many (or all) of these penetrations are driven by separate zero dimensional (point) simulators with proper waveforms and relative timing. Considered as a whole this could be termed a two dimensional simulator.

An example of a three dimensional simulator is a set of sources distributed throughout a volume (with perhaps a conducting medium) in such a manner as to approximate the source current density in an EMP source region.

Another way to group various types of EMP simulators is to label them according to the portions of a system that they drive. Thus a system level simulator is one which illuminates the entire system or at least major portions of it. It is loosely coupled to the system so that various system details are unimportant to the simulator design. From the simulator viewpoint the system is some shape out there of some overall dimensions. A penetration simulator, on the other hand, assumes some knowledge of the scattering properties of the overall system so as to give the proper fields to be produced by the simulator at the penetration. An appendage simulator is intended for driving long conductors such as wires or pipes which connect to a large facility such as a building, a buried site, etc. It is not distributed so as to drive along the entire appendage, but only near the site (or even sites) of interest so as to produce the currents, voltages, impedances, etc. associated with that appendage as they appear at the site of interest. The site itself may be driven (with appropriate timing) by a system level simulator connected to the appendage simulator(s) as appropriate. Of course, in this case the use of the term "system level simulator" does not include the entire system; the entire system includes the appendages as well even though they may be fairly simply describable in electromagnetic terms.

As discussed previously the waveform produced by an EMP simulator is somewhat separable from the spatial field distribution. For a given simulator type one can change waveforms by changing pulse generators (including waveform shaping networks). The simulator electromagnetic geometry basically governs the characteristics of the transfer function from the pulser(s) to the fields, current density, etc. Since different EMP environments (say outside of source regions for example) can have different waveforms then the same EMP simulator type can sometimes be used for different waveforms with a change in pulse generator(s).

For general EMP simulation purposes an incident waveform may look like a fast rise with a smooth decay (say exponential). The rise may be in the several ns range and the decay in the 100 ns to 100 μs range. In some cases (as in radiating simulators) the waveform undershoots, given a typical capacitive generator driving the simulator. However more exotic waveforms such as oscillatory dispersed waveforms (associated with propagation through the ionosphere for example) may be desired. Such cases need special consideration even though strictly speaking they are not a separate EMP simulator type; the pulser (including waveform shaping) is of a separate type and this is part of the total EMP simulation problem. CW excitation gives another quite different "waveform" on the various types of EMP simulators.

EMP simulators are not in general perfect in that they do not exactly reproduce the temporal and spatial dependence of the fields, current densities, etc. associated with a particular nuclear EMP. A "complete" EMP simulator produces the significant features of the spatial and temporal (including frequency spectrum) variation of some type of EMP of interest. It makes a good approximation to the EMP of interest in that the differences between the simulator performance and the EMP of interest (as best known) can be quantified and are acceptably small so that important system vulnerability characteristics are not masked but brought out clearly.

Not all EMP simulators are complete in this sense. As such they might be referred to as partial. Certain performance characteristics may be purposely sacrificed in the design or application of a particular type of EMP simulator because of other significant factors such as cost, mobility, etc. An example of such a tradeoff is the radiating type of EMP simulators such as a pulsed electric dipole driven by a capacitive generator. The low frequency performance is severely limited by the radiation properties of antennas. This is a fundamental and recognized limitation of such devices which is sometimes accepted because of other performance characteristics which are not otherwise attainable in the present state of the art. In particular in this case such a radiating dipole can be carried aloft to illuminate large distributed systems; it also gains significant mobility thereby. Note that the sacrifice of an important performance characteristic should be justified by some other important gain. Removal of low frequencies by inadequate generator design (such as by a low frequency electrical short across the generator) would normally be an unnecessary performance reduction and thus not warranted.

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. The highest quality simulator has the minimum deviation from the ideal 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. The undisturbed simulator fields in this configuration may have various deficiencies. 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.

Another type of figure of merit refers to the interaction of the system under test with the simulator structure. This is basically an issue of the relative sizes of the simulator and system under test. 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.

Each of the categories of EMP simulators discussed in this note is arrived at from its distinctive electromagnetic characteristics. Within each category there are many specific EMP simulator designs. Accordingly each category can be further subdivided and it may be appropriate to do so at some future time when a particular simulator type is better understood. Not only can categories of simulators be further subdivided but more relationships among the various categories may also be found.

Many of these types of EMP simulators have been discussed in previous Sensor and Simulation Notes. Some of them appear for the first time in the notes and are thereby at least partially removed from burial in my notebooks. Hopefully such simulator types will be discussed more extensively in future notes. Not all pertinent notes are referenced because such would make a very large list. Each simulator type is briefly discussed and only the notes with discussions that are fairly general are referenced.

IV. Simulators for EMP Outside of Nuclear Source Regions

One of the most common types of EMP to be simulated is that for which the system is outside the source region. The EMP outside of the source region encompasses a large volume of air and large areas on the surface of the earth compared to the source region volume and corresponding portions of the earth surface. Thus in a single nuclear detonation many systems of interest are exposed to this type of EMP environment. The absence of the local nuclear source region (at the system) also simplifies the EMP simulator problem somewhat. For both of these reasons much work has been done on the design of simulators for this kind of environment and many tests on systems have been performed using such simulators.

Of the different kinds of EMP environments as discussed in section II, the most significant of these outside the source region is that in the air and on the earth asociated with an exoatmospheric nuclear detonation. Figure 2.3 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 fractional μs (a few hundred ns) decay constant (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 as above with only one polarity. The actual EMP environment does cross over at some point in time for a given vector component but the low frequency rolloff 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. Simulators for both of these types of electromagnetic distributions are discussed in this section and the two variations on each simulator type are discussed where appropriate.

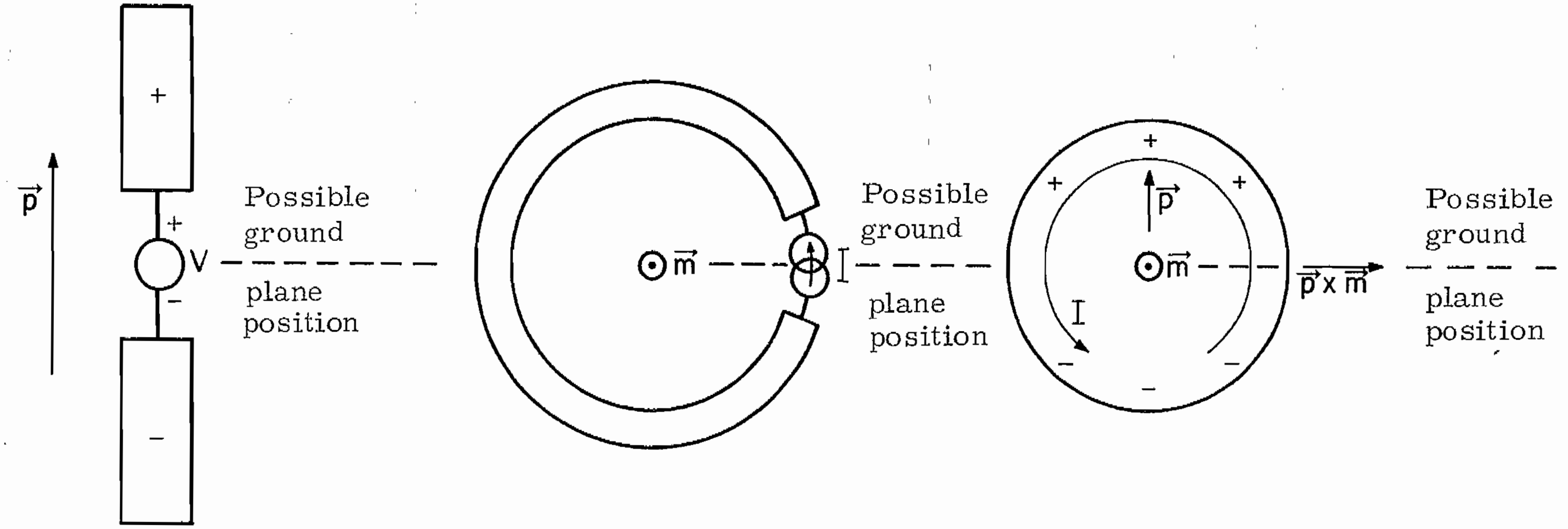
A. Dipole simulators

The class of EMP simulators which 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. In producing a radiated electromagnetic pulse the 1/r 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 achieved since the low frequency radiated fields are so limited for such simulators.

Figure 4.1 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 $\vec{p}$ with a magnetic dipole moment $\vec{m}$ at right angles to each other and related by the speed of light then in the direction $\vec{p} \times \vec{m}$ 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.[10] This $\vec{p} \times \vec{m}$ type of antenna can be used for CW illumination as well as for pulses. A large pulse version of this which uses a ground plane is a simulator type referred to as DILEMMA (DIpole Large Electric and Magnetic Mixed Antennas).

Dipole simulators can be split into two cases. First we have those that are somewhat isolated in free space (away from ground planes, etc.) sending fields in essentially all directions. This may illuminate a system on a ground or water surface from an elevated position and would still be termed a dipole provided its elevation were large compared to its maximum linear dimensions. This allows the dipole fields to be

Note that up to six separate electric and magnetic dipole components can be combined but only four dipole components perpendicular to the direction to the system of interest contribute to the far fields there. Used with a ground plane the four interesting dipole components reduce to two.



A. Electric

B. Magnetic

C. Combined electric and magnetic

Figure 4.1 Types of Dipoles

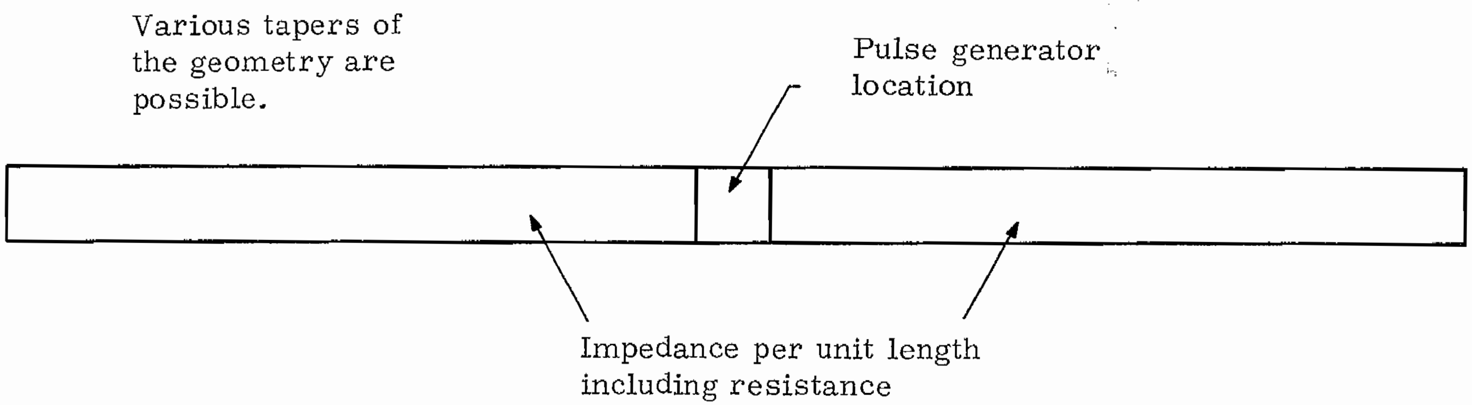


Figure 4.2 Large Impedance Loaded Electric Dipole Shaped Roughly Like a Long, Thin Rotationally Symmetric Structure (RES)

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 (say plane or spherical) in a desired direction.[8] Since a practical array of this type has finite size the ideal wave so constructed only lasts at the observer for some finite time depending on the array size and triggering sequence of the pulsers. The low frequency characteristics of the resulting waveform (including times after the drop in the waveform amplitude) are still limited by the dipole characteristics of the array. Such arrays can be made to approximately focus waves for a very short time by launching a converging spherical wave. For these cases one might use capacitors and switches for the pulsers which are interconnected to form the array, passing current from one pulser to the next. If, on the other hand, appropriate inductances are included with the pulsers the current waveform on the array can be made to ring in damped sinusoidal fashion. By adjusting the capacitance and inductance parameters various frequencies and damping constants can be achieved to make a waveform with a complex frequency which can approximate the natural frequencies of systems of interest (which dominate the system response).[13] Such a simulator could for some complex frequencies be approximately focused on the system so such a technique could be appropriately labelled FOCUS (Fast Omnidirectional Coherent Ultra Simulator). Needless to say such a technique has many limitations when compared to quality EMP simulation.

There are, of course, various types of radiators which are very directional at high frequencies. One type which does not distort the early time shape of the waveform from the pulser is a conical type structure consisting of two or more separate conducting cones of finite length connected to a pulser near the common apex. If the two cones have fairly small angular extent and small angular separation between them such early time directionality is achieved. There are numerous designs one might think of but the use as EMP simulators of all these designs is rather limited.

C. Static simulators

Another class of EMP simulators can be thought of as static simulators. This class could also be termed zero dimensional or point simulators. With this class of simulators the system under test is very close to or even within the simulator structure. As such this is not a radiating type of simulator such as a dipole. It does, however, excite the dipole and higher order multipole responses of the system under test.

The basic limitation of a static simulator is that frequencies are sufficiently small 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. In particular there should be no approximate null in an incident field component of interest near the system location.

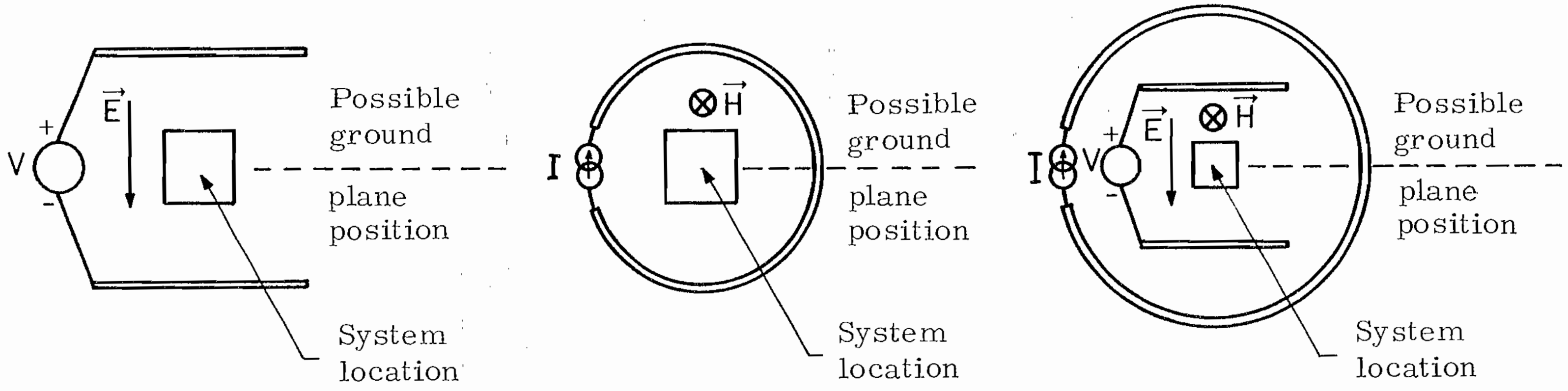
Figure 4.3 shows a few simple designs for this class of simulators. The simplest are those which produce a single component of electric or magnetic field incident at the system. However, up to six orthogonal electric and magnetic field components can be produced with separate waveforms if desired. Figure 4.3C shows a case with one electric and one magnetic field component produced by such a simulator. There are many design sophistications which one can use to improve the uniformity of the various field components. 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.

Note that the total current density in such a simulator is directly related to the electric field by the permittivity and conductivity of the medium used in the simulator around the system under test. For simulating the nuclear EMP outside of nuclear source regions there is typically only a displacement current density $\partial\vec{D}/\partial t$. This class of simulator can also be used for simulating some source region phenomena in which case a conducting medium would be added in the simulator and enclosing the system.

If the system is on an approximate ground plane (including media of comparatively low wave impedance) then for such a simulator only one component of the electric field perpendicular to the ground plane is of interest. Likewise the two components of the incident magnetic field parallel to the ground plane are of interest.

This type of static simulator is also appropriate for driving penetrations (small antennas and apertures) in highly conducting surfaces of systems. The appropriate electric and/or magnetic dipole moments (or higher order moments if the dipole terms are absent) of the penetration are excited with

Note that up to six separate electric and magnetic field components can be combined with various separate waveforms incident at the system location. Near a ground plane this reduces to one electric and two magnetic field components.



A. Electric field (and current density)

B. Magnetic field

C. Example of combined electric and magnetic static fields

Figure 4.3 Static Simulators

the local system surface treated as a ground plane in the simulator design.

D. A class of hybrid simulators

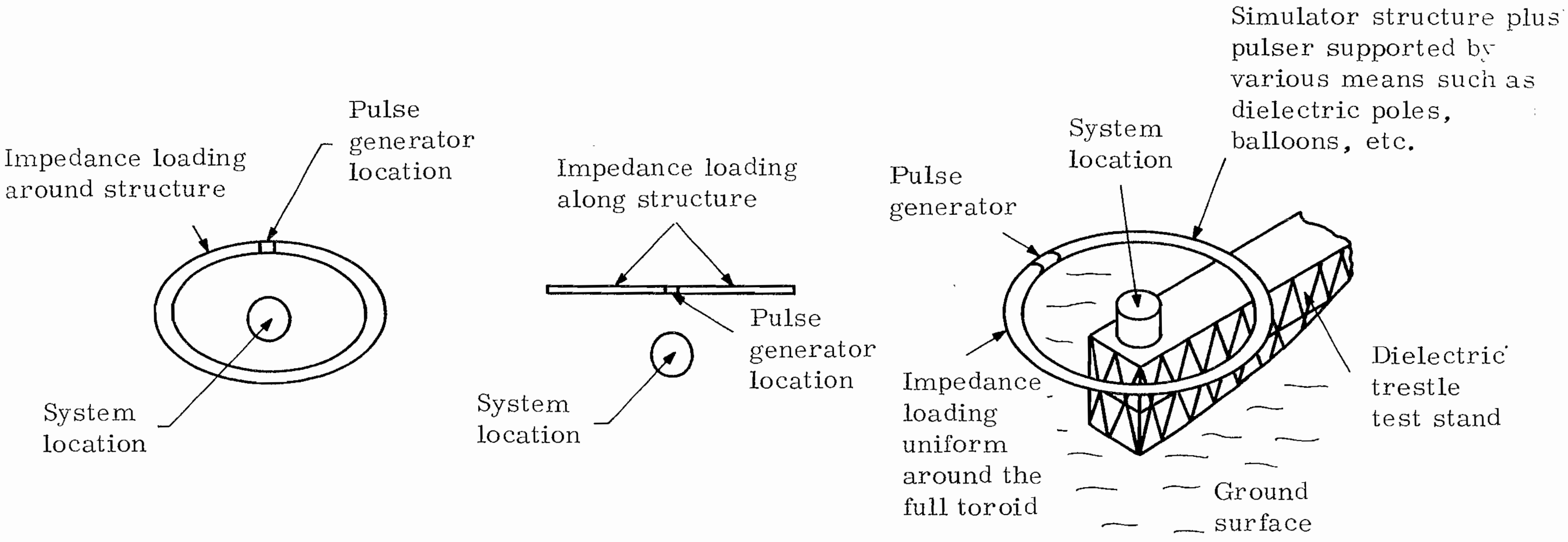
Now let us briefly consider a class of hybrid simulators formed by combining various features of radiating simulators and static simulators. For this simulator concept to apply the system under test should be within or quite near the simulator structure. The basic concept of this class of hybrids can be summarized in three basic characteristics:

1. The early time (high frequency) portion of the waveform reaching the system is radiated from a relatively small source region (or a small number of source regions) 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 sufficiently close to it that the incident static fields are not significantly reduced in amplitude at the system location.

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 of the structure including 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 smoothly become larger to make the fields smoothly transition over to the static field distribution. Thus basically this class of simulator combines early time (high frequency) radiation characteristics with low frequency static characteristics with a smooth transition at intermediate frequencies. In this manner such a simulator can produce electromagnetic fields in the vicinity of the system which have characteristics similar to those resulting from an incident plane wave; the degree to which these characteristics are the same is a measure of the quality of the simulation and this varies depending on various details of the simulator design.

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 figure 4.4, or with a ground plane or earth surface as part of the simulator as shown in figure 4.5.

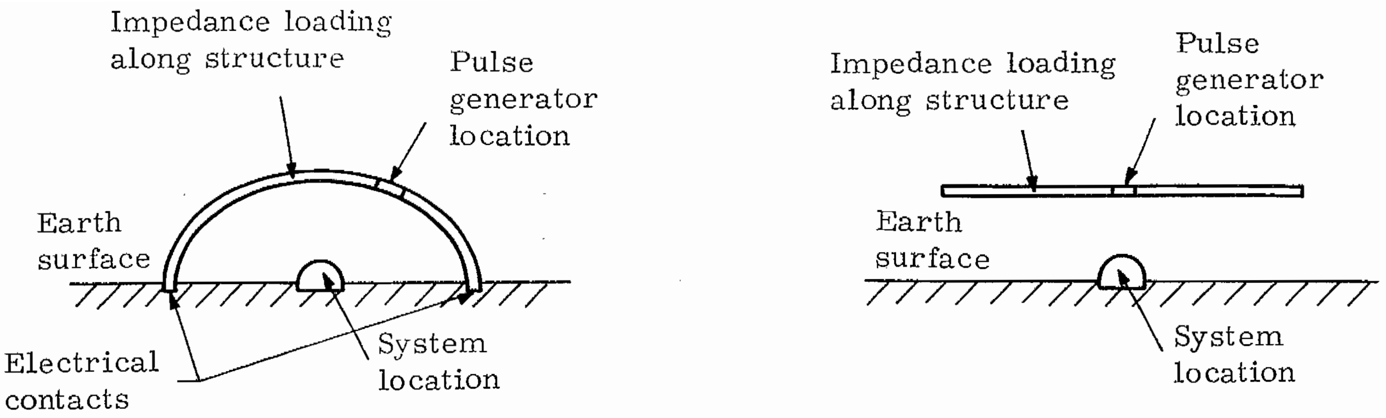


A. General concept with conducting path around system

B. General concept with path around system via electric flux (capacitance)

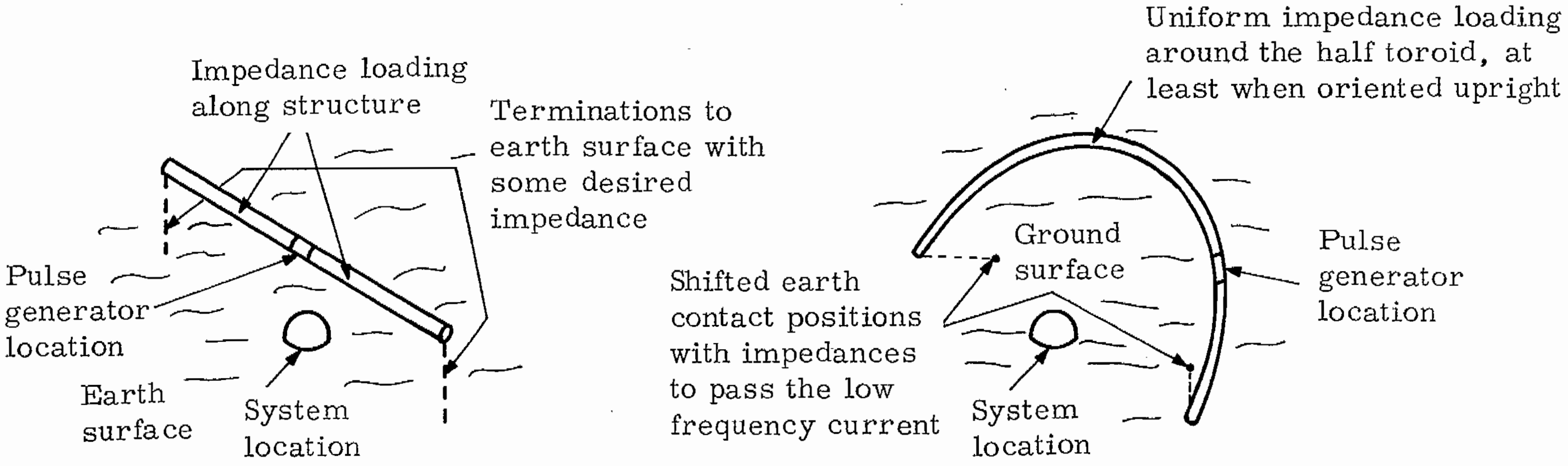
C. Example: TORUS in a full toroid configuration

Figure 4.4 A Class of Hybrid Simulators without Earth Reflection as Part of the 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

Figure 4.5 A Class of Hybrid Simulators with Earth Reflection Included as Part of the Simulation

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. Figure 4.4A shows the simulator structure on a path around the system under test. By using an impedance per unit length around this path which is designed to be a non zero (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.

If the path does not go around the site, such as in the case shown in figure 4.4B, 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. Of course a separate loop structure could be added to make the static magnetic fields correspond better to the static electric fields, but this makes the simulator more complex and the scattering properties of this addition to the simulator structure would have to be included in the simulator design.

A particular type of hybrid is TORUS (Transient, Omnidirectional, Radiating, Unidistant, and Static) which is shown in figure 4.4C in a full toroid configuration as appropriate for simulating an incident plane wave without a reflection from the earth surface.[6] In a real such 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.

Figure 4.5 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 figure 4.5A 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 and a magnetic field parallel 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). Note that for highly conducting earth one can consider this type of simulator as an image problem with the earth surface replaced by a conducting plane (but perhaps with any holes in the earth filled and corresponding portions of the system removed) for some range of frequencies.

In figure 4.5B 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 figure 4.5A is superior to that in figure 4.5B.

Figure 4.5C shows a common type of hybrid simulator which has basically the geometry of a thin structure above and parallel to the earth surface.[7] 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 figure 4.5A, while if the ends are not brought into contact with the ground this simulator is of the type in figure 4.5B. Both types have been built at various places around the country. Note that impedances can be included along the structure and that such impedances are useful for damping the structure if there are no terminations of the structure to the earth at its ends. 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 of the most interesting types of simulator in this class of hybrid simulators is TORUS as shown in figure 4.5D. For use in conjunction with the earth surface TORUS consists of a half toroid connected to the earth surface with a pulse generator and impedance loading along the toroidal arch.[6] The system under test is located roughly midway between the positions that the two ends of the half toroid reach the earth surface. Note that for low frequencies such that the skin depth in the earth exceeds the major radius of the toroid one can shift the current path into the ground such that it enters at a position which compensates for the low frequency magnetic field distortion associated with the finite earth conductivity. By varying the positions that the half toroid meets the earth surface, the lean angle of the half toroid, and the position of the pulse (or CW) generator one can simulate a free space plane wave (with earth reflection) incident on the system with all angles of incidence from the upper half space and all polarizations. Thus besides having the basic requirements for this class of hybrid simulators which include ground reflection TORUS also has flexibility in that such a simulator can be used to simulate a wide variety of EMP cases.

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 compared to cross section dimensions to wavelengths 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. Such structures have 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 field 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 figure 4.6. 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 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.[3]

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. 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 making 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 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.

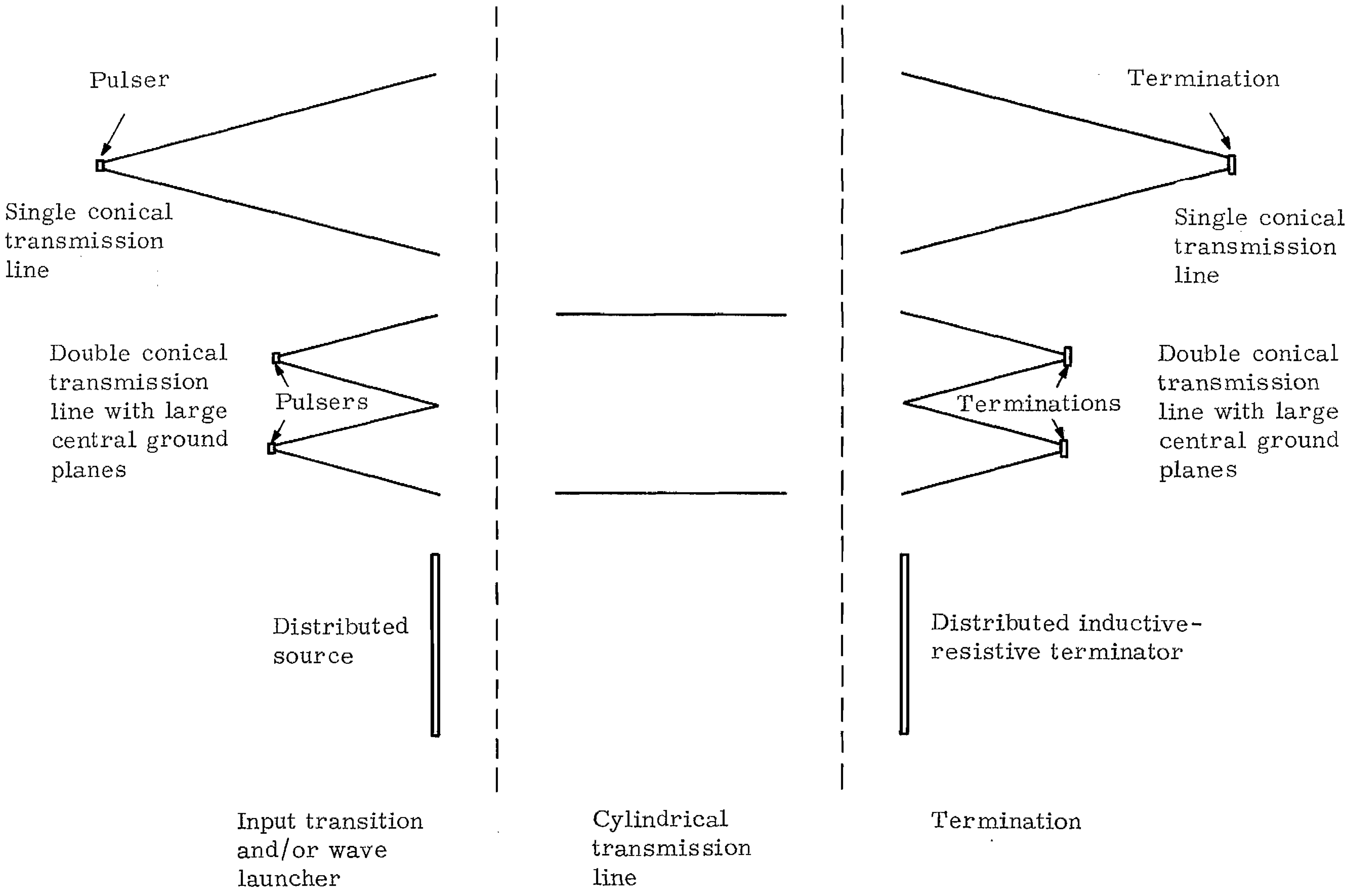


Figure 4.6 Some Optional Designs for a Two-Parallel-Plate Transmission Line Simulator: View Parallel to Plates and Perpendicular to Direction of Propagation

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 distributed 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 an open circuit 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.

As examples of such transmission line simulators one can consider figures 4.7 and 4.8. These are continuations from two older existing transmission line simulators, ALECS and ARES (names of specific simulators not types of simulators), which have been used primarily for EMP tests on missiles in their in-flight configuration. The new simulators of this type under design at present, namely ATLAS I and II, are primarily intended for EMP tests on aircraft.

In figure 4.7 the simpler simulator, ATLAS II, is shown in one of its design configurations. This simulator is very much as ARES in design, only considerably larger. It is a vertically polarized, horizontally propagating, transmission line EMP simulator. The vertical polarization refers to the direction of the electric field in the working volume between the plates and above the dielectric trestle test stand. There is a single pulser or pulser array and there is a single termination. The bottom plate is much wider than the top plate and lies on the earth surface. This minimizes the effect of the earth on the propagation and helps shield the instrumentation beneath the bottom plate.

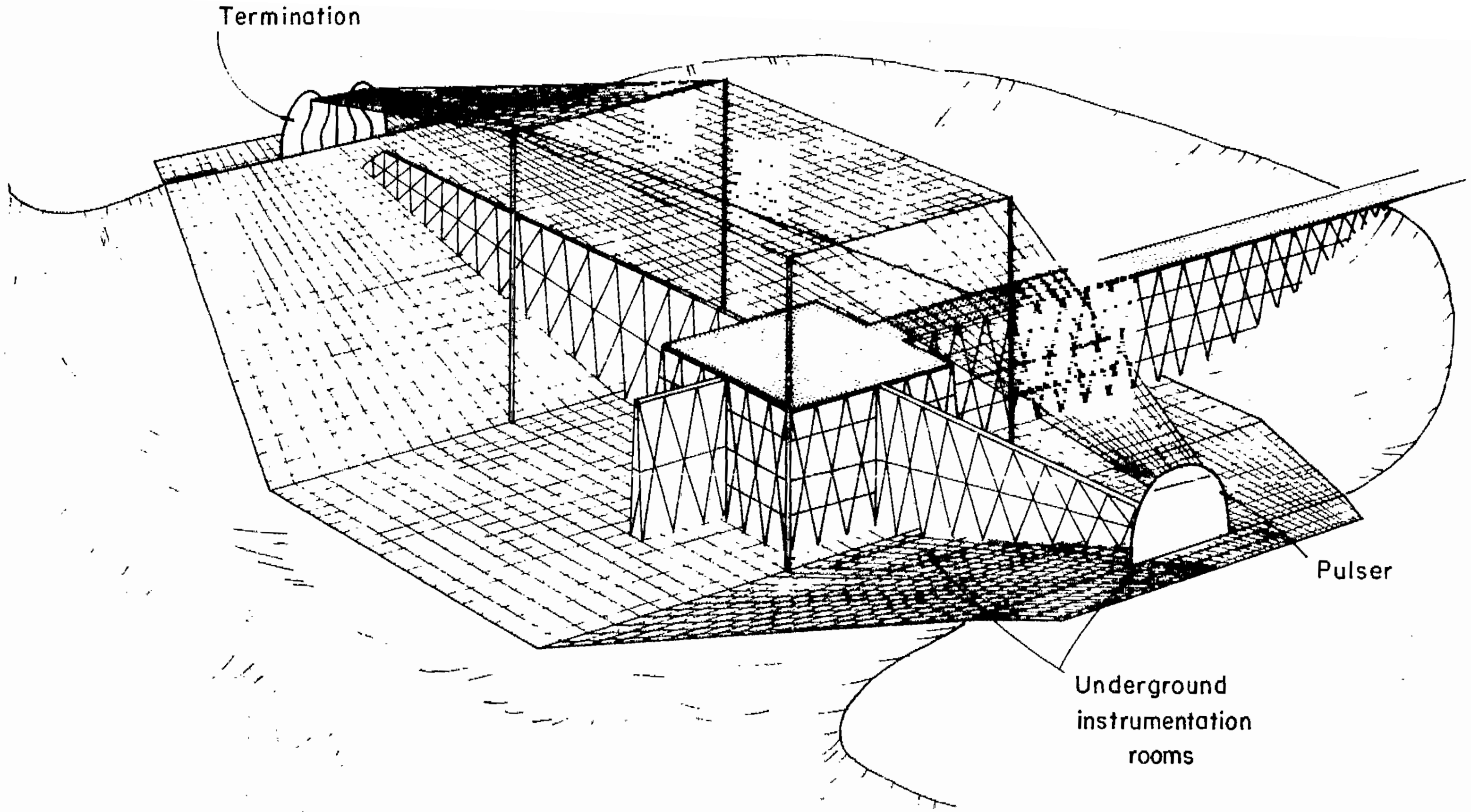


Figure 4.7 ATLAS II, Design I, in a Particular Orientation

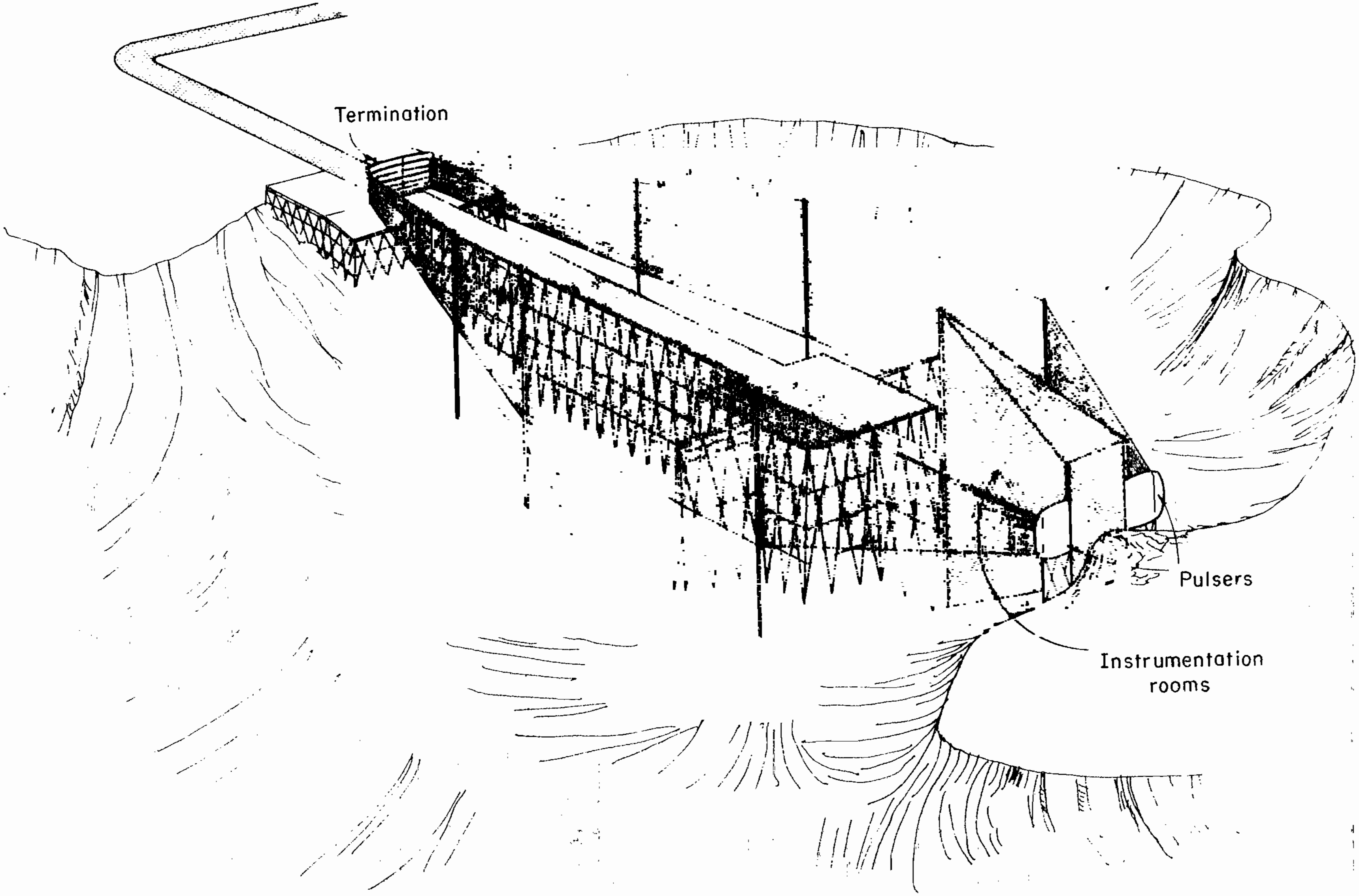


Figure 4.8 ATLAS I, Design I, in a Particular Orientation

Figure 4.8 shows ATLAS I in one of its design configurations. It is a horizontally polarized, horizontally propagating, transmission line EMP simulator. There are two pulsers or pulser arrays driving two conical transmission lines which eventually join to each other and then to the cylindrical transmission line. There is a single output transmission line leading to a termination which also has a center tap leading to the earth to terminate any common mode on the simulator structure. The working volume lies between the cylindrical transmission line plates on top of the dielectric trestle test stand. For such a horizontally polarized transmission line simulator the presence of the ground surface is undesirable and so care must be taken to raise the height of the transmission line (and also working volume) as high as practical above the ground surface to minimize the interaction of the transmission line fields with the earth.

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 if only a not very large surface area on the earth surface needs to be illuminated with the simulator fields. Such a guided wave simulator would be useful for simulating the EMP propagated in a ground wave to a system at the earth surface.

Transmission line structures have also been used and/or proposed for parts of simulators which, however, are very poorly terminated. Reflections are allowed to occur at the earth surface, at the transmission line conductors, etc. producing undesired (and unnecessary) reflections in the waveform, thereby also distorting the frequency spectrum of the waveform in an undesirable manner. Such are low quality EMP simulators which are not suitable for high quality, high confidence EMP testing.

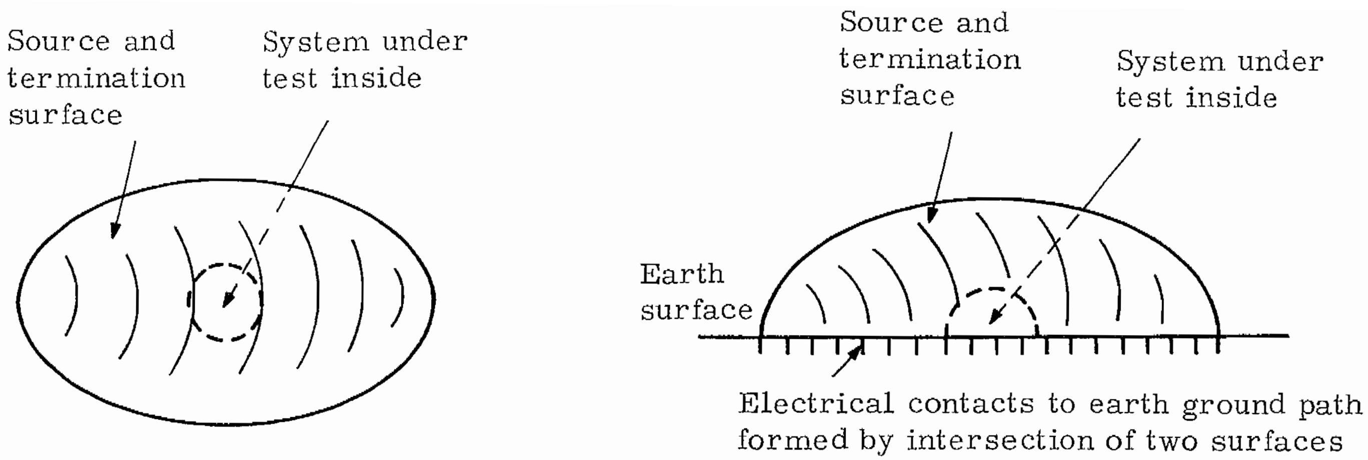
Here one should also mention that for transmission line simulators certain types of systems may operate tied to conducting ground planes; in such cases one of the plates of the transmission line can be that ground plane and the system can be appropriately tied to it. However, the direction of incidence 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 I hope to get to it 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.[9] . 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.

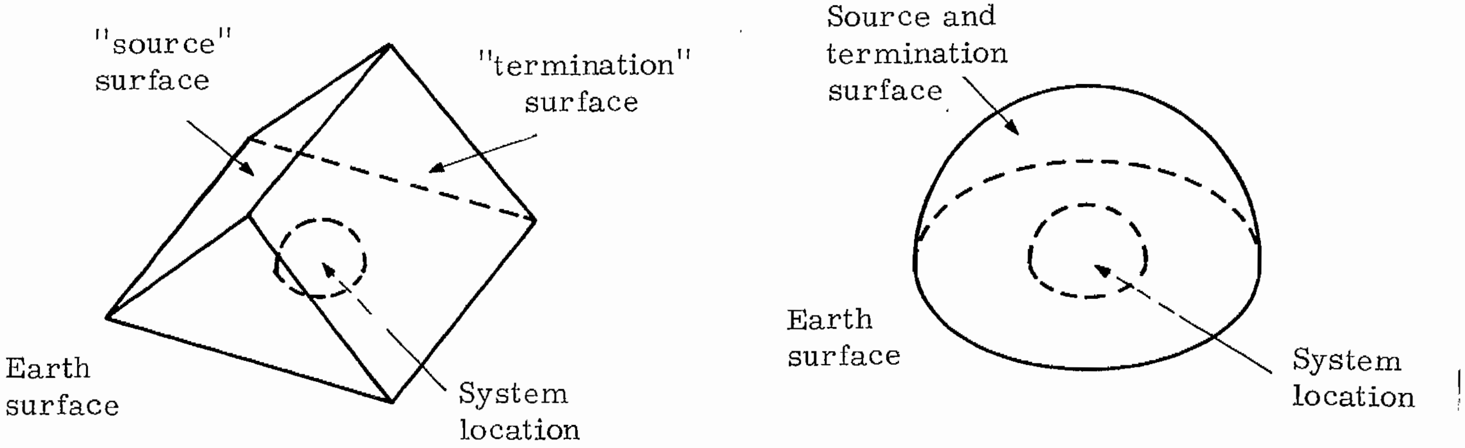
Typically the tangential electric field is what one would specify on the boundary. A low impedance electric field source can be approximately realized at high frequencies (early times) by a distribution of capacitive pulse generators with timed switches. However, not all portions of the bounding surface 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 figure 4.9A.

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



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

Figure 4.9 Distributed Source and Termination Enclosing System figure 4.9B. Having specified the incident plane wave and calculated the resulting earth reflection then the tangential electric field from the sum of these two waves on the surface of interest above and in contact with the earth surface gives the required field to be produced. Again this surface is in general a combined source and termination surface. 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.

Figure 4.9C shows a particular geometry for such a simulator with an earth reflection included. In this case one might put distributed pulse generators on one sloped face of the prism shaped surface and distributed inductance and resistance on the other sloped face. With appropriate angles between the faces and the earth surface and appropriate triggering sequence for the sources, one sloped face can roughly be thought of as a source surface and the other as a termination surface. However, this is only a very crude approximation. The geometry of figure 4.9D with a hemisphere over a ground is interesting because it can be treated analytically in the approximation that the earth is perfectly conducting using a spherical coordinates eigenfunction expansion. This is one case that the ideal distribution of tangential electric field and surface current density can be studied in detail.

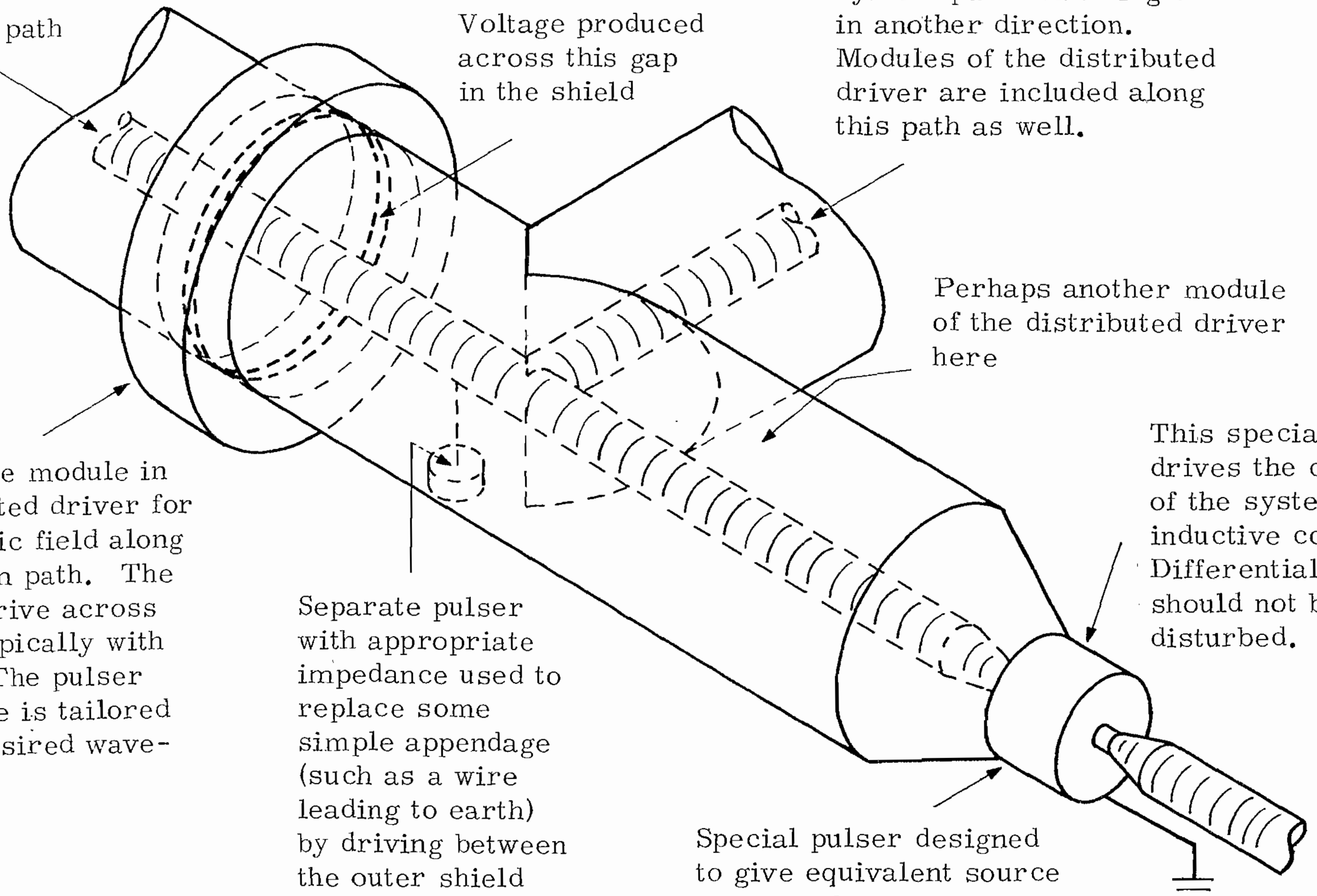
This class of simulators with a closed source and termination surface has an advantage in that one can ideally vary direction of incidence and polarization somewhat arbitrarily. The polarization of the incident plane wave (before ground reflection) can in principle be made to rotate as a function of time. However, in a practical realization of such a simulator such flexibility will be limited somewhat and the resulting field distribution will have non ideal components (perhaps significantly non ideal). Note that this class of simulators can be related to the class of cylindrical TEM transmission lines with separate source and termination surfaces at each end of the transmission line. Such a simulator class has part of its boundary surfaces as distributed source and termination while other parts are waveguiding transmission line conductors. In the class of simulators considered here such waveguiding conductors have shrunk to zero except in special cases where part of the simulator surface is perfectly conducting and parallel to the direction(s) of propagation.

G. One dimensional simulators

As briefly mentioned in section III a one dimensional or line simulator is most appropriate for use with a system which can be approximately localized to a one dimensional path. This system path is idealized in figure 4.10 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. Note that this tube is just an idealized boundary and many things may be inside. 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 figure 4.10. 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.

For the case of a system path above and parallel to the earth surface the incident tangential electric field including earth reflection can be readily approximately calculated. Resistively damped capacitive generators can give many of the desired waveform characteristics when driving an inductive structure (basically the inverse of a current sensor) which forms part of the distributed driver. The vertical component of the incident electric field including earth reflection does not have low frequency cancellation like the horizontal components. So the resulting waveform is a little different making the driver design somewhat different with much more inductance required in the inductive coupler, say by using transformer



System path

Voltage produced across this gap in the shield

System path branching off in another direction. Modules of the distributed driver are included along this path as well.

Perhaps another module of the distributed driver here

This special pulser only drives the common mode of the system path by inductive coupling. Differential impedances should not be greatly disturbed.

This is one module in a distributed driver for the electric field along the system path. The pulsers drive across the gap typically with cables. The pulser impedance is tailored for the desired waveform.

Separate pulser with appropriate impedance used to replace some simple appendage (such as a wire leading to earth) by driving between the outer shield and system path

Special pulser designed to give equivalent source series voltage in system path to account for part of system path which is not driven

Note this connection to earth if appropriate to preserve common mode impedance

Figure 4.10 One Dimensional or Line Simulator techniques including bifilar winding, etc. 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, say by adding a resistive impedance in parallel with a low inductance. If one goes sufficiently low in frequency the inductance still dominates the conversion of current from the pulser to driving electric field thereby establishing some lower frequency of usefulness for such a pulser, at least in the case of simulating the incident electric field perpendicular to the earth surface.

Note the outer conducting tube surrounding the system path as indicated in figure 4.10. 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.

Referring back to the electric field integral equation that one might use to analyze the system response the electric field from the distributed drivers corresponds to the incident electric field in the integral equation. The Green's function in the integral equation basically corresponds to the various self and mutual impedance terms between one part of the system and another, with earth effects included as well if appropriate for the particular system. This Green's function should be kept roughly the same as far as the net result on currents on the system when the simulator is added to the space around the system.

The addition of this outer conducting tube is certainly one of the fundamental limitations of this simulation technique and its effects should be quantitatively understood in each case. The reason that one does not grossly disturb these 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 say, then one can estimate the change in this logarithm and try to keep this change acceptably small.

Another way to look at a one dimensional simulator is to consider then the system tube as one side of a transmission line. This transmission line is driven so as to give distributed electric field (voltage) sources effectively in series with the system tube and current sources between the two transmission line conductors as would appear in the usual set of coupled transmission line equations with sources.

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 oscillate in some prescribed manner. Note that the system path may include branches as indicated in figure 4.10 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 figure 4.10 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. Hopefully this large portion of the system can be more simply modelled, say because it does not have the transformers, switches, etc. such as were intentionally included inside the simulator. Note that for this type of generator at an "end" of the simulator as shown in figure 4.10 the source impedance should be small compared to the common mode impedance. This is to allow the impedance of the system in common and differential modes for those portions of the system outside the simulator to directly be the impedances loading the portions of the system inside the simulator just as if the simulator were not there. This assumes linearity for the portions of the system outside the simulator and if this assumption is not valid such effects can be included to some extent in the design of the pulser(s) at the end of the simulator.

This one dimensional or line type of simulator is a rather new concept and unfortunately I have not had time to write a detailed note on the subject. I hope to write such a note in the not too distant future. While such a simulator does nor give the highest quality EMP simulation it still has certain distinct advantages. First it allows one to drive certain portions of large distributed systems up to high levels ("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. Clearly much work needs to be done in understanding the details of one dimensional simulators and the associated equivalent generators.

H. Complex waveform generators

Now let us briefly discuss some of the issues involved in complex waveform generators where the desired waveform is not simply a fast rising, smoothly decaying, single polarity waveform (for a particular incident field component). This is not a type of simulator per se but a type of pulse generator (including associated wave shaping elements) which can be used to drive various of the simulator types we have been discussing to obtain other kinds of waveforms but with the same spatial characteristics at each frequency as discussed before. It is basically just the amplitude and phase associated with the fields that is changed, but uniformly for the fields everywhere they are generated by the simulator. Viewed another way the simulator transfer functions are still the same. Again we are considering only cases of EMP outside of nuclear source regions.

There are various ways that a distorted incident EMP waveform can arise. For example the EMP from a surface burst, air burst, or high altitude burst is distorted as it propagates over the earth horizon (as seen from the detonation point). This introduces some high frequency loss in the waveform. Furthermore the wave is reflected up and down in the earth ionosphere waveguide. This produces a somewhat oscillatory waveform. Such waveforms can be approximately synthesized with pulsers driving somewhat lossy oscillatory circuits and such waveforms can have the required appropriate frequency domain characteristics as well. However, very little effort has been given to generating waveforms for this type of EMP because other types of EMP waveforms have much larger amplitudes in time and frequency domains. These more significant waveforms are relevant for the same systems in the air and near the earth surface, but of course arise from detonations closer to the system.

Another type of distorted waveform is that resulting from an incident EMP propagating up through the ionosphere. One of the most interesting of such cases is that of a high altitude

EMP waveform as shown in figure 2.3 propagating toward some exoatmospheric system which is not being exposed to the direct γ rays and X rays from the same detonation. The wave that reaches the exoatmospheric system is quite dispersed in time. One can crudely think of this waveform by letting the highest frequencies arrive first in time with the lowest frequencies arriving last. Below some ionospheric cutoff frequency essentially no frequencies propagate through. Note that different frequencies propagate by different paths (not straight lines) in going through the ionosphere, complicating matters somewhat. The earth's magnetic field further influences the propagation. Furthermore the high electric field strengths associated with the EMP incident on the ionosphere introduce nonlinear, time dependent properties into the ionosphere.

Considering only a rather simple model of the ionosphere and neglecting such factors as nonlinearities and the effects of the earth's magnetic field one can see some ways to reproduce the ionosphere effects in waveforms. For example a simple plane stratified ionosphere can be reduced to a set of transmission line equations for a nonuniform equivalent transmission line. One could think of building such a transmission line and adding the appropriate elements (inductance and resistance between the transmission line conductors) in a distributed manner. Similarly one could use the lowest order mode above cutoff in a conventional type waveguide (hollow conducting waveguide) with perhaps appropriate resistive losses added. However, in both such cases the structures become prohibitively large. There are other more complicated structures which one can think of building to give roughly the same dispersion as the ionosphere. One approach to generating the desired dispersed waveform is then to first generate the simpler waveform such as is incident on the ionosphere (allowing for 1/r geometrical reduction of amplitude) and then passing this waveform through such a dispersing filter. The problem here is making a practical but adequate dispersing filter which appropriately disperses the waveform into the desired oscillatory one with changing frequency and with time duration out into say the ms time frame.

An alternate approach to the generation of such dispersed waveforms involves first noting that the peak amplitudes of such waveforms are not in the 10^5 V/m range but in the 10^2 or 10^3 V/m range. Then using active, time varying electronic circuits one can generate low level waveforms which can then be amplified up to much higher levels using high power, linear, broadband amplifiers. Generating the small signal amplitude dispersed waveform can be accomplished in various ways. One might generate the oscillating waveform with time dependent oscillation period in a resonant circuit with time varying elements; this waveform could in turn be amplified with a time varying gain to establish the desired waveform envelope.

A more elegant way of generating such a small amplitude dispersed waveform involves starting with a simplified ionosphere description to which one can obtain at least approximate analytic solutions for the dispersed waveform. Such an ionosphere approximation might be a uniform slab. Note then that the solution in terms of known functions satisfies a differential equation with time varying coefficients (say a modified form of Bessel's equation). One can solve such an equation by analog computer techniques. The time varying coefficients become time varying gains. The little specialized analog computer must operate, however, on a real time basis implying components which operate to quite high frequencies. Note that the ionosphere parameters of electron density, collision frequency (if included), and slab thickness all enter as constants in the differential equation. As such these parameters can be readily changed in the analog computer by changing various settings thereby varying the dispersed waveform over ionospheres of interest.

This dispersed waveform question is comparatively new in EMP simulation. I hope to get out a note on this subject in the not too distant future; these waveform generation and dispersal concepts have been lying around in my notebooks for some time now. One should note that a partial simulation can be achieved by testing the exoatmospheric system using an undispersed waveform (allowing for the appropriate amplitude reduction). However there are certain nonlinearities and time dependent characteristics in system responses that can possibly make the dispersed waveform more significant in some cases. For completeness one would then like to have such a dispersed waveform capability. Again note that this is not a question of a new type of EMP simulator but of a new type of pulse generator which can drive various types of EMP simulators. Such a new type of pulse generator could be used somewhat interchangeably with other more conventional pulse generators on various individual existing or planned EMP simulators.

V. Simulators for EMP in Nuclear Source Regions Near the Earth Surface

Having considered the various types of EMP simulators for simulating EMP environments outside source regions let us now go on to consider simulators for EMP in nuclear source regions. 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.

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.[12] 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 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 (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.

Simulators for EMP in source regions near the earth surface are then more limited in capability at present than those for EMP outside of source regions (discussed in section IV). Nevertheless some significant progress has been made with some simulator types built and design concepts for some new types also developed.

A. Buried transmission line

An important simulation technique for the close-in EMP near the earth surface is the buried transmission line.[2] As shown in figure 5.1 this is the two conducting plates or sets of conducting rods that go into the earth approximately perpendicular to the earth surface with separation ℓ, width w, and depth d. Considering just the buried transmission line for the moment, it is driven near the ground surface by some pulser connected between the two plates. At low frequencies the wave propagates down into the earth in a TEM mode guided by the buried transmission line with the wave impedance given by the wave impedance of the medium. The propagation into the earth is attenuated in a skin depth fashion much as in the case of an infinite distributed source that the nuclear source region represents above the earth surface (including just below the earth surface as well).

As one goes to lower and lower frequencies the skin depth in the earth approaches d and a reflection comes back from the open circuited bottom of the transmission line. However due to the lossy characteristics of the propagation this is a very smooth process with no resonant peaks or nulls in the frequency domain (for real ω). However for skin depth greater than d the E/H ratio in the earth is higher than in the ideal case of an infinitely long buried transmission line. Of course the low frequency form of the nuclear source region above (or just into) the earth surface (which gives the fields in the earth to be reproduced) is not uniform due to $1/r^2$ and γ-ray mean free path attenuation. Then also the desired low-frequency fields in the earth deviate from such an ideal case. Thus there is not much improvement made by having d much longer than a few times the γ-ray mean free path. Of course one can change the impedance terminating the buried transmission line by adding elements to the bottom of the line if one is willing to tunnel down and across the distances involved.

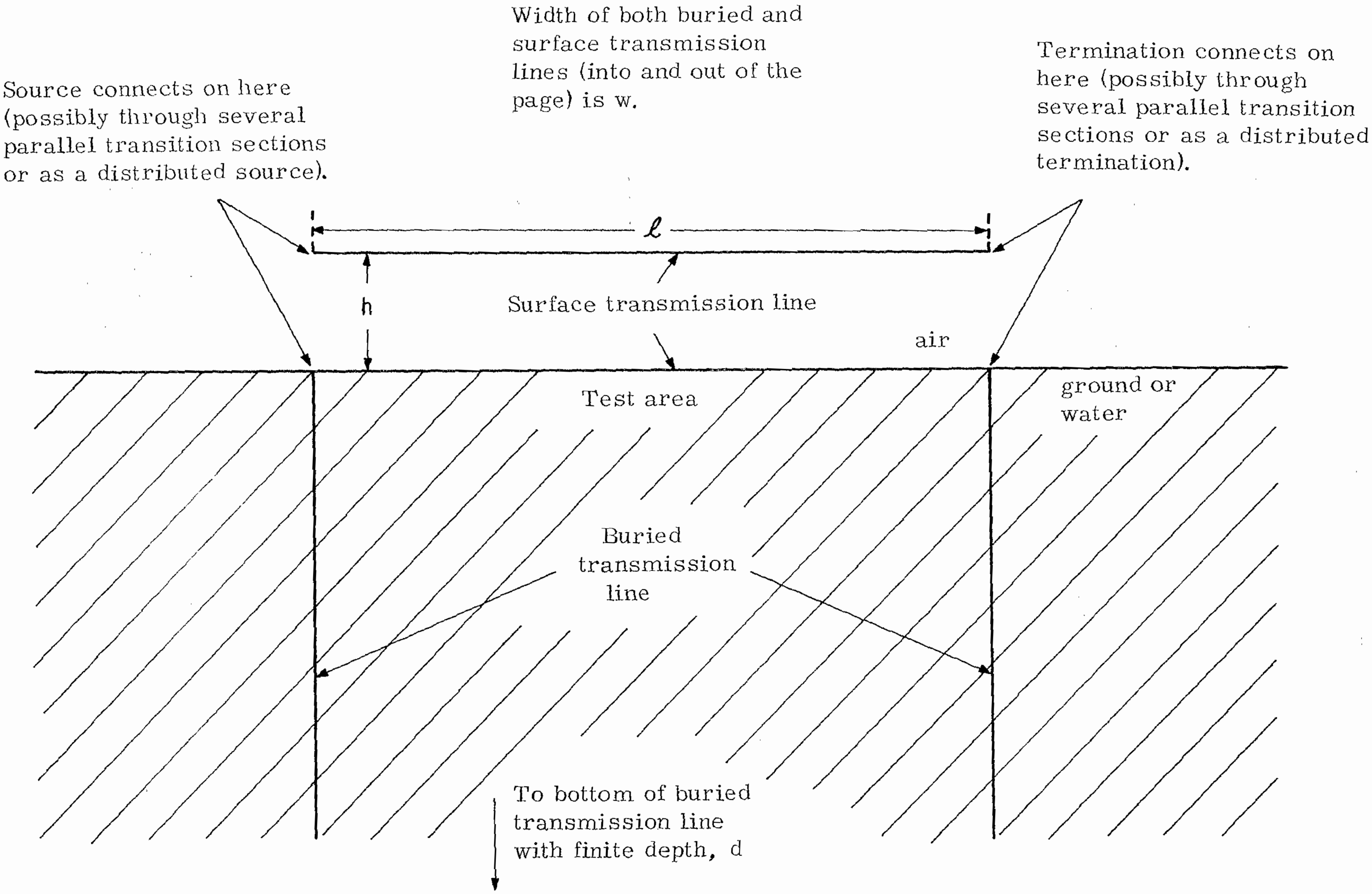


Figure 5.1 SIEGE: Combined Buried and Surface Transmission Lines

The buried transmission line can be combined with other techniques which are oriented toward high frequencies. These will be discussed later. The buried transmission line can also be used in the context of simulating EMP outside of source regions as well if one desires low frequency fields with good distributions deep into the earth. The buried transmission line can be connected, for example, to hybrid simulators which connect to the earth in two places. In such cases structures other than ones which approximate two flat plates are more appropriate.

The buried transmission line is particularly appropriate for illuminating buried or partly buried "hardened" sites of various types. Note that if long conducting appendages leave the buried site and leave the region driven by the buried transmission line then such conducting appendages can be electrically connected to the buried transmission line with appropriate pulsers so as to simulate the effect of a long appendage in driving the site.

B. Surface transmission line

Next consider the surface transmission line shown in figure 5.1.[4] It consists of a conducting plate (approximated by wires, tubes, etc.) of width w, length ℓ, and at a height h above the earth surface. Such a structure supports a wave propagating between the conducting plate and the earth surface. At high frequencies (with radian wavelengths still of the order of h or less) this wave propagates parallel to the earth surface with speed approximately the speed of light in the upper nonconducting medium (air). This wave is quasi TEM in the upper medium and in the limit that the earth conductivity becomes infinite it is pure TEM. This wave does have some attenuation in propagating the length ℓ because of the finite earth conductivity. This attenuation can be reduced by increasing h, but at the expense of reducing the field amplitude for a fixed voltage (or even a fixed power) driving the surface transmission line. One can improve some aspects of this problem by sloping the surface transmission line to make it nonuniform, i.e. by gradually decreasing h as one moves along the line from source to termination. If this is done its effects should also be included in designing the termination for the surface transmission line to account for both high and low frequencies.

The surface-transmission-line characteristic impedance varies slowly with frequency, increasing toward low frequencies because of the longitudinal impedance associated with the earth. However, if ℓ is not too long, or h too short, or the conductivity and/or permittivity of the earth too small, then the surface transmission line can be terminated in its characteristic impedance with the earth conductivity assumed infinite. The high-frequency reflections will then be small and the low-frequency reflections will come in smoothly as frequency is decreased. Such low-frequency reflections will then also be insignificant except for frequencies low enough that radian wavelengths are large compared to ℓ. For such low frequencies the field distribution in the upper medium is quasi static so that reflections are not distinct but blend in with the incident wave to give a smooth field distribution.

The surface transmission line provides a simple technique for obtaining a high-frequency, large-amplitude (if desired) wave propagating at a speed about c over the earth surface. It does not include the source current density and conduction current density terms as in the case of a nuclear surface burst. As such it gives a partial simulation, basically for the magnetic field. If the surface transmission line is used for simulating EMP outside of source regions, say for high altitude EMP incident on the earth surface, then the complete set of angles of incidence and polarization are not compatible with this technique. However, surface bound EMP waves with approximately vertical electric field polarization (outside source regions) can be simulated quite well with a surface transmission line.

C. SIEGE

Combining the buried and surface transmission lines gives an EMP simulation technique referred to as SIEGE (SImulated EMP Ground Environment). This is shown in figure 5.1. The basic operation of the surface and buried transmission lines has already been discussed. A SIEGE simulator merely combines them with a pulser (or CW source) at one end of the surface transmission line and a generally resistive termination at the other end of the surface transmission line as indicated in figure 5.1. Note that in driving a SIEGE type of simulator the pulser is connected onto the surface transmission line. However the buried transmission line is still driven by the pulser because the pulser is connected to the buried transmission line directly in one place and through the top plate of the surface transmission line plus the termination in another place. SIEGE type simulators have already been used on various occasions for EMP tests on systems intended to survive in nuclear source regions.

Because of the limited simulation characteristics associated with the surface transmission line in that the source current, conduction current, and conductivity in the upper medium are not present as they would be in the case of a nuclear source region, SIEGE does not provide complete nuclear source region simulation near the earth surface. Nevertheless the important features of the magnetic field can be reproduced in SIEGE as long as the desired magnetic-field amplitude is not too large such that the associated electric field (with E/H roughly 377 Ω in the upper medium) does not exceed the breakdown strength of air or any high-dielectric-strength gases used. The desired magnetic field strength depends on how close to the nuclear detonation the system of interest is supposed to be (and how large the detonation is supposed to be) for our case of interest.

D. Simulators with a low conductivity medium plus a distributed source and termination surrounding the system

One of the problems in simulating the EMP in a nuclear source region is to produce a conduction current with the associated conductivity of the medium around the site. This can markedly change some of the system interaction processes.

If the desired conductivity σ of the medium above the earth surface is not too large (corresponding to systems near the fringes of the nuclear source region) then a type of simulator can be used such as is described in figure 5.2. Here a distributed source and termination surface is used surround the portions of the system above the earth surface. The distributed source and termination is attached to the earth via a set of electrical contacts on a path around the system site.

In section IV.F a plane wave with ground reflection in air was discussed. Now add a medium of low conductivity with permittivity and permeability approximating those of free space within this source and termination surface, above the earth surface, and surrounding and in electrical contact with the system to be tested.[9] In such a medium a high frequency wave can propagate at nearly speed c. If the attenuation across the site is not too large (because of the low conductivity) then one can produce a roughly vertically polarized quasi TEM wave propagating roughly horizontally across the site. Note that the conductivity of the medium above the earth surface would best be small compared to the earth conductivity for the earth surface to be considered a low impedance boundary for the quasi TEM wave. At low frequencies such that the wavelengths or skin depths, as appropriate, are large compared to the simulator size the field distributions become quasi static so that the low-frequency E/H ratio can be adjusted to values (non quasi TEM wave) if desired.

In the medium above the earth surface there is a conduction current density which is approximately vertically polarized. This has some limitations vis a vis a nuclear source region which has a conduction current density in the air with

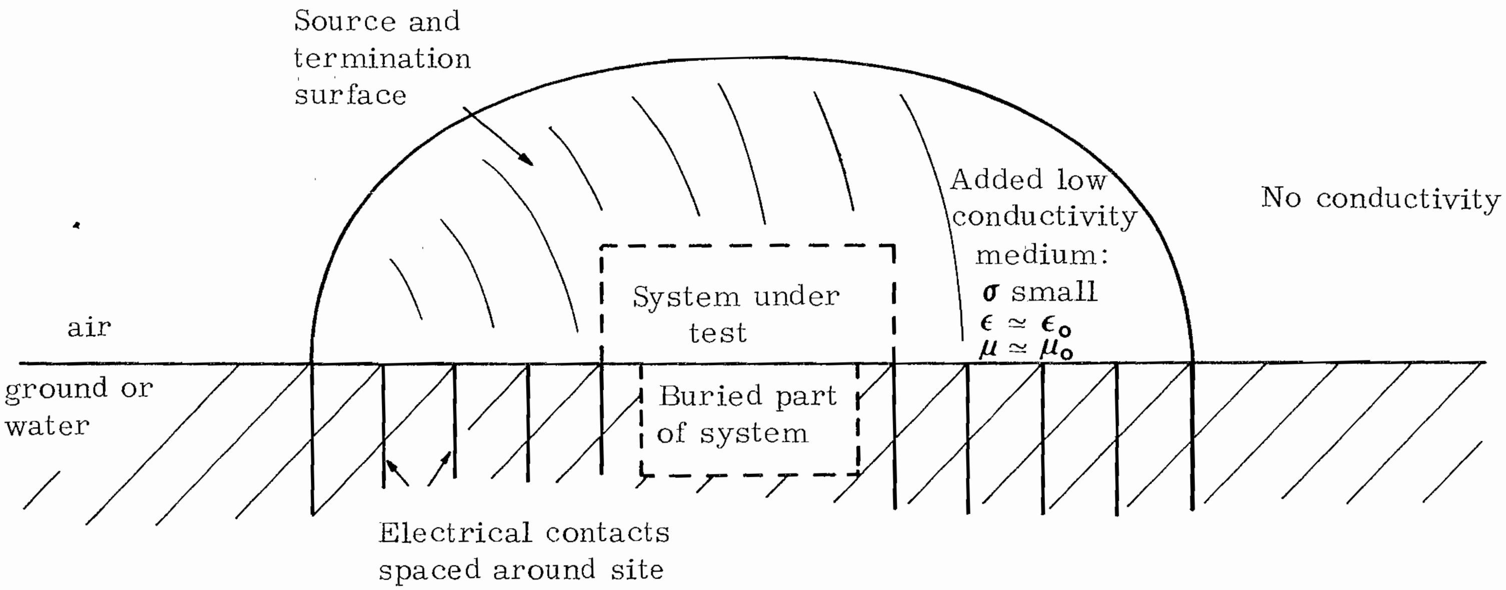


Figure 5.2 Distributed Source and Termination Bounding a Low-Conductivity Medium

significant vertical and horizontal conduction (plus displacement) current density components. However, this type of simulator represents a step in the direction of more complete simulation of the nuclear EMP as found in nuclear source regions near the earth surface.

E. DISCUS

Another type of simulator for the close-in EMP near the earth surface is DISCUS (DIstributed Source Conducting-Medium Underground-System Simulator) as illustrated in figure 5.3.[5] As with SIEGE this type of simulator uses a buried transmission line to give the approximate desired fields propagating down into the earth around the system site.

An essential new part of this type of simulator is the finely gridded 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. Needless to say this relatively high conductivity is meant to approximate the conductivity of the nuclear-source-region air in an average sense over the significant parts of the EMP time history. With a relatively highly conducting medium above the earth surface this medium must be relatively thin (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 (within a meter or so) 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 $\mu \simeq \mu_o$.

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. This gives part of the divergence of the horizontal current density thereby contributing to a vertical current density component (especially at lower frequencies) similar to that in the corresponding nuclear source region.

As time progresses during the pulse and the corresponding important frequencies are lowered, the fields penetrate significantly into the conducting earth. To provide these slower

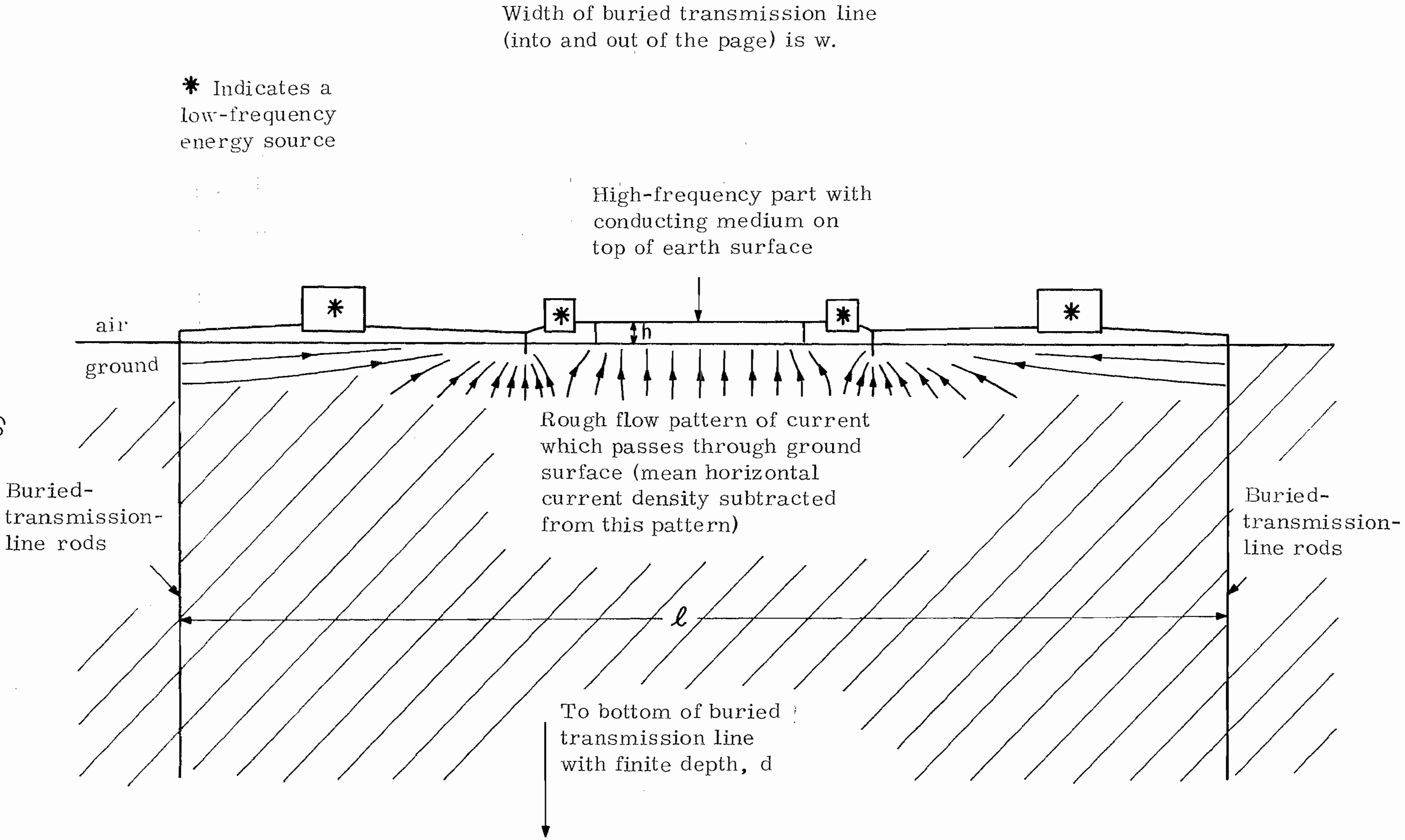


Figure 5.3 DISCUS with Both a High-Frequency Finely Gridded Distributed Source, Driving a Conducting Medium, and a Low-Frequency Coarsely Gridded Distributed Source

rising fields in the earth, large low-frequency energy sources are positioned over the remainder of the site. These pulsers are connected to the buried transmission line and to the fast distributed source covering a part of the site as discussed above. These slower sources are also triggered at speed c across the site in the desired direction of propagation. Just as with the fast distributed source these slower pulsers can give out smaller amplitudes as one progresses across the site to simulate the falling off of the source current density amplitude in a nuclear source region. For this purpose electrical contact to the earth is provided between the slower pulsers to allow for current flow across the earth surface at such positions.

DISCUS has an advantage over SIEGE in that the E/H ratio above the earth surface at locations of concern is kept small (compared to the free space impedance) because of the relatively highly conducting medium. This more adequately simulates the nuclear source region EMP characteristics. Furthermore it allows one to go to larger magnetic field amplitudes without having electric fields break down the air or other insulating medium, thereby allowing one to simulate the EMP closer to nuclear detonations. Of course the conduction (plus displacement) current density and associated conductivity are also included in this type of simulation. Needless to say DISCUS is a more complex type of simulator (and more difficult to build) than SIEGE. However, DISCUS does not include the source current density of high energy electrons running through the medium above the earth surface, the earth near the earth surface, and those parts of the system near the earth surface.

F. Static simulators

As discussed in section IV.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 figure 4.3 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. A medium of appropriate 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. Note that such added conducting media should have a permeability $\mu \simeq \mu_0$.

Static simulators are basically low frequency devices for which wavelengths or skin depths (as appropriate) are larger than the simulator dimensions. For relatively highly conducting media the limitation is one of skin depths. For a given size of simulator then as the conductivity of the added medium is increased the maximum operating frequency of the simulator as a static simulator is decreased.

G. One dimensional simulators

One dimensional or line simulators as discussed in section IV.G can also be applied to the problem of simulating EMP in a nuclear source region near the earth surface. The medium surrounding and in contact with the conductors along the system path and also in contact with the outer conducting tube (although perhaps not in continuous contact with the outer conducting tube) can be made to have a desired conductivity with permeability $\mu \simeq \mu_0$. The geometry of such a simulator is shown in figure 4.10. The basic addition is just the conducting medium.

Note that the distributed drivers need to be spaced closer together for a given maximum frequency of interest. This is due to the addition of the conducting medium and the accompanying reduction of the magnitude of the complex radian wavelength (skin depth). Furthermore the radius of the outer conducting tube may need to be decreased for the same reason. Of course the impedances which the various distributed pulsers and other special pulsers drive is also considerably changed by the addition of the conducting medium.

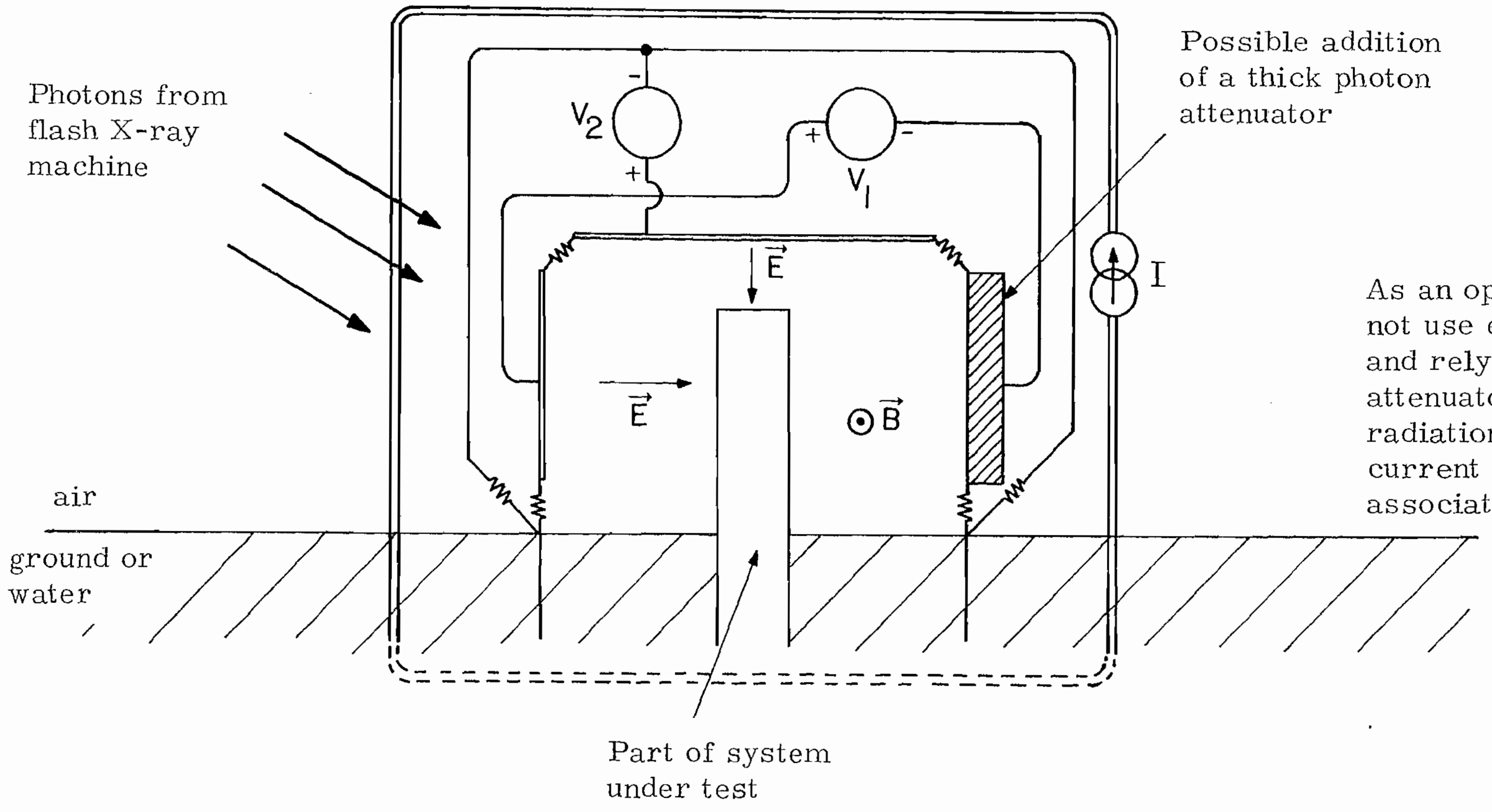
There are various types of systems or system appendages near the earth surface on which such a one dimensional simulator might be used for EMP tests. An example might be power lines leading into a site. Another example would be various types of long, thin protrusions extending vertically out of the major parts of the system portions which are buried in the earth.

H. Inclusion of pulsed photon sources with EMP simulators driving small systems, system penetrations, or system appendages

The types of EMP simulators considered so far in this note have a common characteristic in that none of them have the current density of high energy electrons like that in the nuclear source region. It is this source current density and the associated ionization which generate the EMP in the nuclear source region. One can generate such a source current density of high energy electrons by illuminating the site with high energy photons of energies similar to the γ rays (and X rays to some extent) associated with an appropriate nuclear detonation. Confining ones attention to pulsed sources of high energy photons other than nuclear weapons then the amount of photon energy in the pulse is fairly limited. However, source current densities of high energy electrons can be produced by such means with desired amplitudes and pulse widths over volumes of space which are considerably smaller than typical nuclear source regions near the earth surface. Depending on the amplitude of the photon pulse desired one can illuminate various volumes and associated cross section areas. However, only at very low amplitudes can a pulsed photon source of such a type drive a large system. As one considers the higher amplitudes of interest for the photon pulse the limited present technology will only allow small volumes to be exposed to the large amplitude photon pulse. This limits ones attention to small systems, system penetrations, or system appendages.

Figure 5.4 shows a pulse of high energy photons, say from a flash X-ray machine, incident on some part of a system near the earth surface. This figure shows how a pulsed photon source might be combined with a static (zero dimensional) EMP simulator. One can try to use the high energy electrons themselves to generate the desired fields but this requires the inclusion of the proper boundary conditions around the volume of interest because this volume is not the same as the full nuclear source region which generates the EMP to be simulated. The thick photon attenuator roughly on the opposite side of the volume from the incident photons provides a step in this direction. However, the fields in a nuclear source region near the ground surface depend on the diffusion depth (or skin depth) of the fields in the conducting air. When the diffusion depth gets to be larger than the simulator volume such use of photon attenuators does not give complete simulation. One might then make some of the boundaries of the volume of interest at various potentials using low impedance sources so as to somewhat independently control the electric field and current density (conduction plus displacement) components. Likewise the magnetic field can be controlled using loops driven by appropriate pulse generators. Note that the presence of the source current density of high energy electrons ionizes the air (as in the nuclear source region) so that the air need not be replaced by a special conducting medium provided that the time history (and energy spectrum) of the photon source is adequate and provided that care is taken with the choice of the simulator materials and structure placed around the system.

Sources for static E field are only indicated schematically. In actual practice they would be positioned on the sides (in and out of the page as seen in this view).



As an option one might not use electrical sources and rely only on photon attenuators to control the radiation driven source current density and associated fields.

Figure 5.4 Photons from Flash X-Ray Machine Driving a Small Part of a System at the Earth Surface in a Static Simulator Configuration

Likewise the one dimensional (or line) simulator discussed in sections IV.G and V.G can be combined with pulsed photon sources. A one dimensional EMP simulator such as illustrated in figure 4.10 can be modified to include such pulsed radiation sources. However, for fairly lengthy system paths in the one dimensional simulator the volume to be irradiated by the pulsed photon sources (i.e., the volume inside the outer conducting tube) can be fairly large requiring a rather large photon pulse generator or many such generators. Again the resulting source current density of high energy electrons can be used to make the air conducting as in the appropriate nuclear source region. The presence of the source current density and conductivity also influences the design of the distributed pulsers and other special pulsers which are part of a one dimensional simulator.

VI. 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. 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 in-flight 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 V.D this type of simulator was discussed for a source region near the earth surface. That case was illustrated in figure 5.2. It is a direct extension from the case with a nonconducting medium (air) surrounding the system as discussed in section IV.F. The basic idea is to propagate a wave through a medium of low conductivity, and thus with acceptably small loss, by constraining the electric field tangential to a surface enclosing the system to have the desired form.[9] The present case differs from that in section V.D 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. Static simulators

Static (or zero dimensional or point) simulators can also be used for simulating EMP in nuclear source regions in air. This type of simulator has been discussed in section V.F for the case of nuclear source regions near the earth surface. In air away from the earth surface this type of EMP simulator does not need to take account of the earth presence in its design. Figure 4.3 shows some of the various possibilities for configurations of such static simulators. Of course, in the present case there should be a medium of appropriate conductivity included just as in the case discussed in section V.F.

C. One dimensional simulators

One dimensional (or line) simulators can also be used for simulating EMP in nuclear source regions in air. The comments here are much the same as in section V.G except that the long, slender system path is not near the earth surface. The techniques are the same and section IV.G and figure 4.10 can be referred to for more details. Note that in the present case a medium of appropriate 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.

D. Inclusion of pulsed photon sources with EMP simulators driving systems

For the case of a nuclear source region in air one can simulate the EMP through use of pulsed photon beams in a manner similar to that described in section V.H in connection with nuclear source regions near the earth surface. As indicated in figure 5.4 static (or zero dimensional) simulation techniques can be combined with a pulsed high energy photon source to more completely simulate the nuclear EMP. Such pulsed photon sources can also be combined with one dimensional simulation techniques (as illustrated in figure 4.10) in a manner much the same as discussed in section V.H.

Figure 6.1 shows an interesting test geometry for simulating the presence of a system in a nuclear source region in air. This can be considered a zero dimensional simulator with pulsed photon source as mentioned above. The photons pass through a reference ground plane with atomic number (Z) about that of air. The photon beam and resulting electrons are mostly stopped by the thick photon attenuator on the other side of the system under test. Between the two there are electric field, source current density, conduction current density, and displacement current density all perpendicular to the two conducting surfaces (in the absence of the system to be tested). Except for the fringe capacitance (and possibly fringe conductance) outside the illuminated test volume the geometry gives a uniform electromagnetic field configuration in the two transverse directions with no magnetic fields in the test volume. This is very similar to the simplified spherically symmetric air burst geometry in which there are only radial components of electric field and current density with no magnetic field. In both cases Maxwell's equations reduce to a single first order differential equation involving current density and electric field.

The fringe effects at the outer edge of the photon attenuator can be reduced if so desired by the addition of pulsers giving specially tailored waveforms around the test volume connecting the front conducting boundary to the photon attenuator. This technique is somewhat similar to the guard ring techniques used in designing precision capacitors. Note that for this special simulation geometry one can think of going beyond the limitations of static simulators toward high frequencies because of the special form of Maxwell's equations that results. For completeness, though, in extending this technique to small wavelengths (or small skin depths) the generators around the test volume would have to be distributed as a surface enclosing the test volume and triggered at speed c to match the photon propagation through the test volume.

The air density in the test volume can of course be varied to simulate various altitudes. However, low air densities lead to large electron ranges which make the pulse of high energy electrons in a high altitude nuclear source region lag behind the pulse of high energy photons because of the slower electron speeds and angular spread of the various electron trajectories. To simulate this effect the front conducting boundary can be replaced by a fine wire grid (screen) which emits few electrons. Then electrons from portions of the air near the photon source can be allowed to pass through the front grid, or these electrons can be removed by various electromagnetic field distributions and a separate controlled electron beam can be emitted by a separate source and passed through the front grid. More such grids may be useful in the drift region for controlling the electron beam.

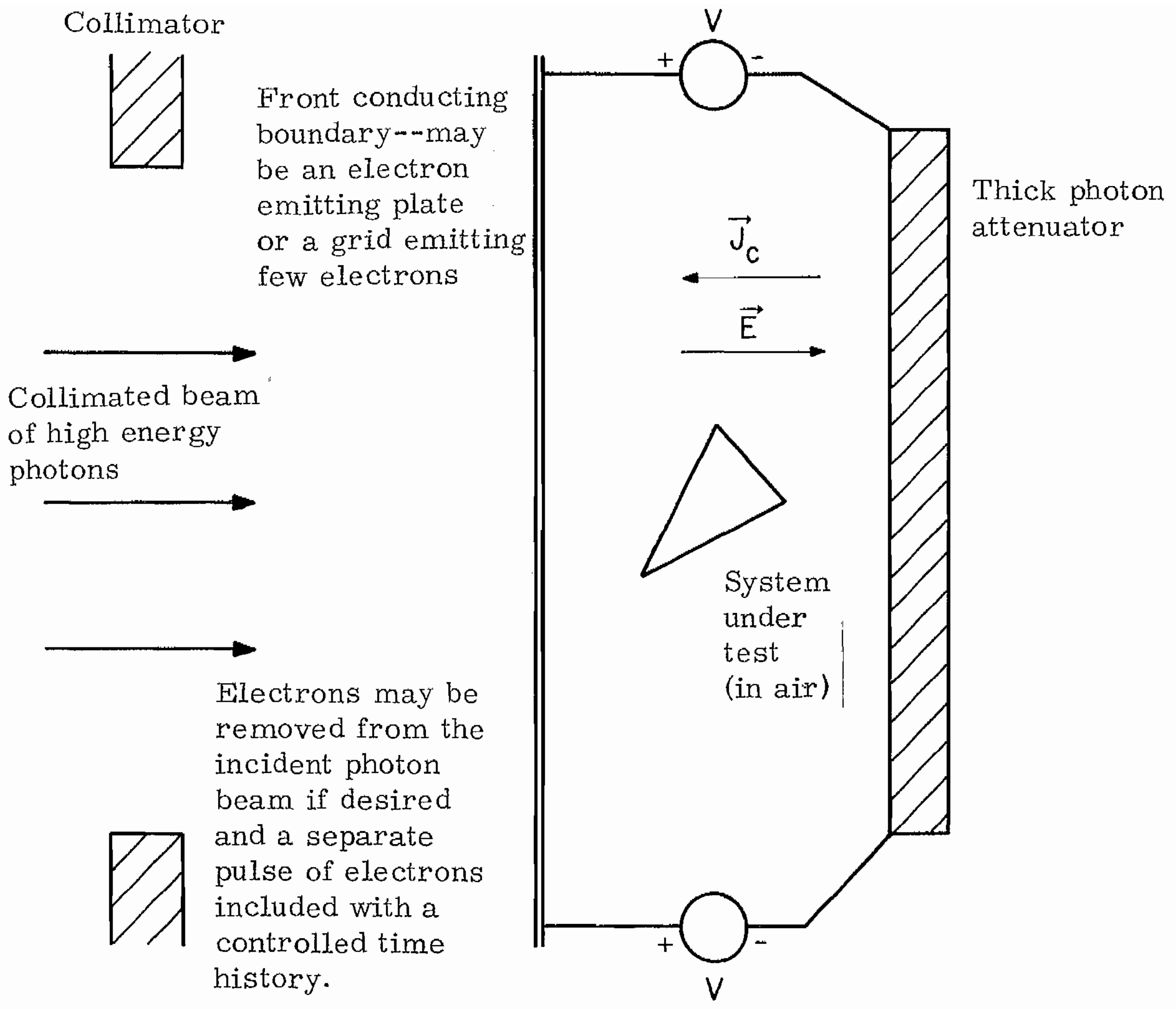


Figure 6.1 Photons from Flash X-Ray Machine Driving a System in Air

At high altitudes the earth's magnetic field significantly bends the electron trajectories. By appropriate controlled DC magnetic fields in the simulator some of this trajectory bending can be simulated, but to a fairly limited degree in small size simulators. Again the direction of electron beams can be changed by appropriate pulsed electron sources propagating an electron beam in the proper direction. The direction of such an electron beam can also be changed by localized field geometries produced outside the test volume.

The test volume would likely be a part of a much larger chamber in which the air density can be changed. If this chamber is basically a closed metal shield then it would be advisable to introduce loss which damps the cavity resonances. Such loss could be introduced by resistively loaded electric and magnetic dipole antennas on the inside surface of the large cavity. These antennas could also be connected together to form a resistively loaded grid structure attached to the conducting wall at many places through resistors.

This special EMP simulator geometry shown in figure 6.1 can also be thought of as just a special case of various geometries involving pulsed photon beams driving reference conducting boundaries (or cavities) and various positions and shapes of photon attenuators. Using such techniques various electromagnetic distributions are possible.[1]

VII. Simulators for Systems Generated EMP in Exoatmospheric Regions

Exoatmospheric systems such as satellites have a special type of EMP environment when exposed to the γ rays and X rays from an exoatmospheric nuclear detonation. This is the systems generated EMP associated with the high energy 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 characterized by $\vec{J} = \sigma\vec{E}$ where σ is a matrix or is 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.

For exoatmospheric systems there are various intensities of photon pulses of interest. Not much work has been done on building full scale simulators for this type of EMP. There are, however, various approaches one can use for designing such simulators. The basic approach is to have the electrons travelling through an approximate vacuum just as in the real case; such an approach gives the most complete simulation. Less complete simulation consists of producing currents and charges on the system of the same magnitudes, waveforms, distributions, etc. as would have resulted had the appropriate electrons been ejected so as to follow their proper trajectories.

Since the effects of the fields on the ejected electrons are rather significant the numbers and spectra of electrons ejected are important. If pulsed photon sources such as flash X-ray machines are used to illuminate the system and thereby eject these electrons it is then important that the pulsed photon source have photon numbers per unit area, spectra, and waveforms which reasonably approximate the γ rays and X rays from the nuclear weapon of interest.

A. Simulators for exciting the interiors of systems which have a highly conducting outer cover by using pulsed photon sources

If one considers the special case that one is basically concerned with an interior electromagnetic problem because of the presence of an outer conducting shield (so that only relatively small electrical signals are associated with coupling of signals from the exterior) then the simulation problem considerably simplifies. This type of an EMP is a subset of the systems generated EMP (or SGEMP) known as internal EMP (or IEMP). This type of EMP can be simulated fairly simply in comparison to the external type of SGEMP for the same simulation quality.

As shown in figure 7.1 the system is illuminated with a pulsed photon source of appropriate amplitude, pulse shape, and photon spectrum. The system forms its own test volume. One may wish to control the static magnetic field due to the earth in the vicinity of the system and of course control the air density (or density of other gases), perhaps through a separate gas enclosure (or vacuum enclosure) around the system. Also the electromagnetic shield which is the system exterior plus other materials on the shell such as coatings, etc., should be at least one electron range thick for the highest energy electrons produced by the incident photons so that electrons do not penetrate into the system from its exterior. If the shell is not this thick then special techniques can be used to keep the exterior electrons from striking the system such as by the use of static electric and magnetic fields inside the outer gas enclosure to appropriately deflect such electrons out of the photon beam.

B. Simulators for exciting both interior and exterior portions of systems by using pulsed photon sources

If one wishes to excite the exterior currents and charges on the system as well as the interior currents and charges then the simulation technique involving a pulsed photon source as illustrated in figure 7.1 should be significantly improved. In some cases there is no clear distinction between the exterior and interior of a system and so the more difficult requirements associated with the exterior currents and charges are the important requirements.

Figure 7.2 illustrates some of the features which can be incorporated into a simulator which starts with a pulsed photon source to simulate the systems generated EMP on an exoatmospheric system. Starting with the incident photon beam it should be collimated so that photons not travelling so as to reach the system on a direct path are removed and do not unnecessarily strike the vacuum chamber walls. The electrons in this photon beam need to be largely removed. The various sources of electrical noise near the photon pulser and associated with the photon beam conditioning need to be shielded, say by a sparse conducting grid, from the volume around the system. The area on the vacuum enclosure which is behind the system from the incident photon beam is illuminated by both the photons from the pulser and electrons scattered from the system. This part of the vacuum enclosure could be recessed away from the system to form a "get lost" hole as well as having static electric and magnetic fields present to minimize electron backscatter toward the system. On all the inside

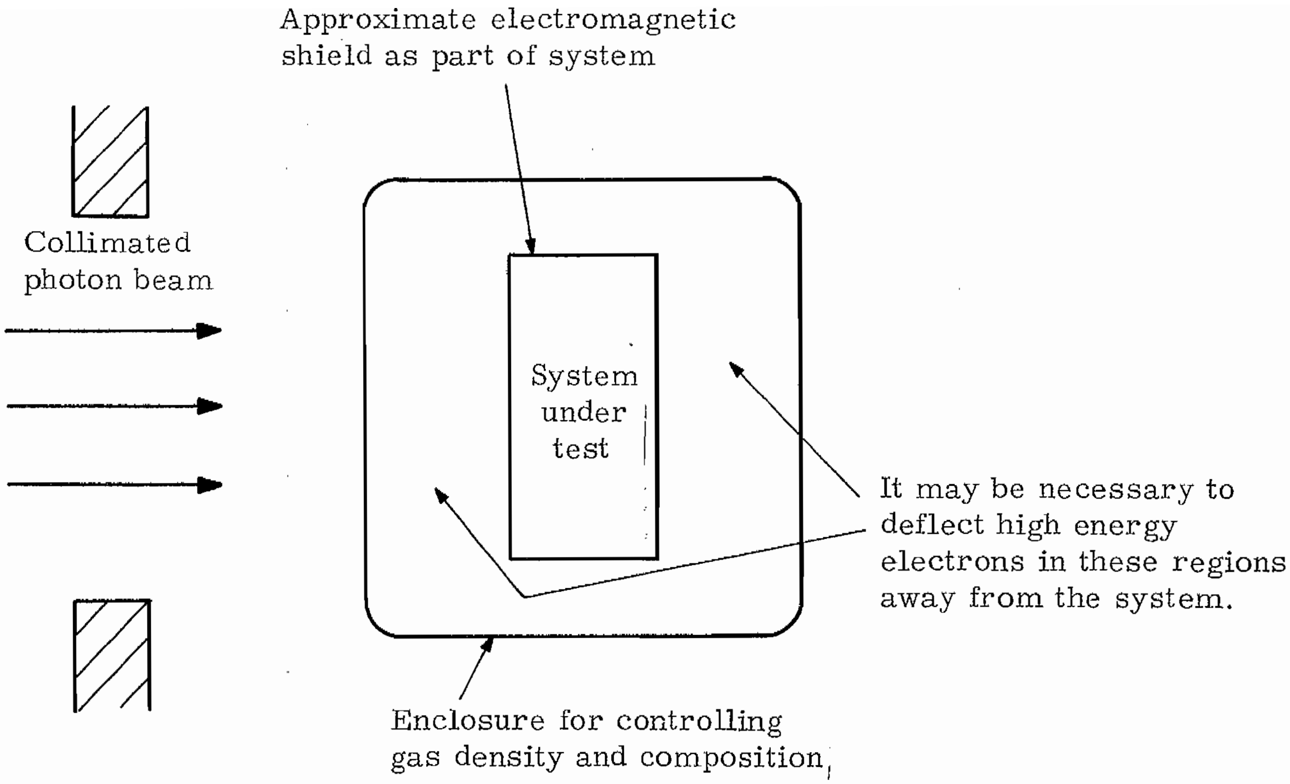
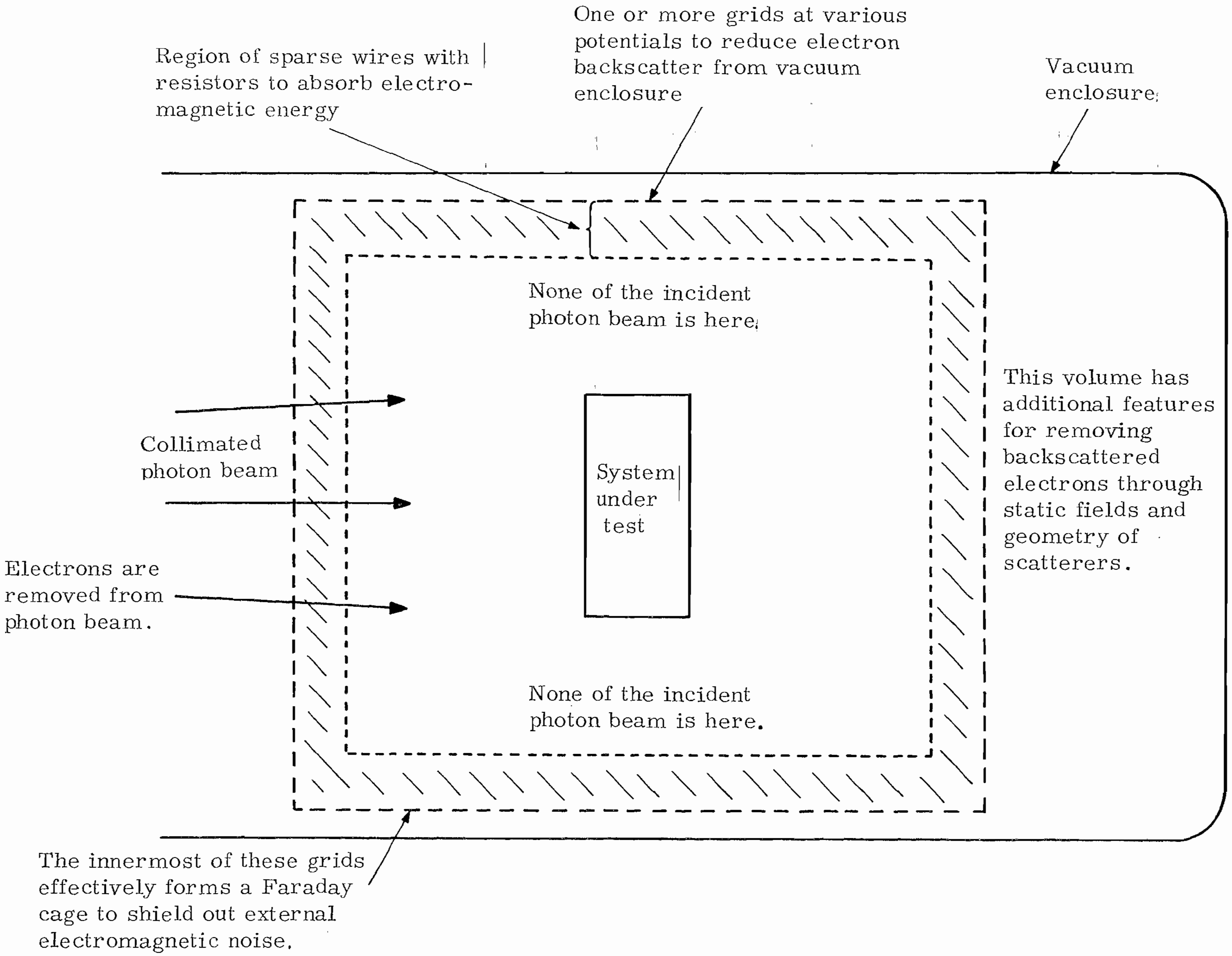


Figure 7.1 Photons from a Flash X-Ray Machine Driving an Approximately Electromagnetically Enclosed System



Region of sparse wires with resistors to absorb electromagnetic energy

One or more grids at various potentials to reduce electron backscatter from vacuum enclosure

None of the incident photon beam is here.

This volume has additional features for removing backscattered electrons through static fields and geometry of scatterers.

Electrons are removed from photon beam.

None of the incident photon beam is here.

The innermost of these grids effectively forms a Faraday cage to shield out external electromagnetic noise.

Figure 7.2 **Photons from a Flash X-Ray Machine Driving an Exoatmospheric System in a Test Chamber with Properties Approximating Free Space**

surface of the vacuum enclosure one might include suppression devices to minimize electron backscatter from the electrons arriving from the system. The use of electrically biased grid structures can trap the lower energy electrons without the grids themselves being significant sources of backscattered electrons because of their sparse structures.

A system inside a vacuum enclosure does not have the same electromagnetic situation as the same system in free space. If the chamber was dielectric (including under photon and electron irradiation) then the chamber would not have a large electromagnetic effect. However, grid structures for reduction of electron backscatter do have a large electromagnetic effect. Let us assume that a continuous metal (steel, aluminum, etc.) vacuum enclosure is used. This obviously has big electromagnetic effects which need to be reduced. First, the system has a capacitance to infinity in free space and a corresponding equivalent radius (by comparison to a sphere). The capacitance between the system and the vacuum tank (including internal grid structures and resonance damping structures) is greater than the free space capacitance. The fractional capacitance increase should be made acceptably small. The vacuum tank resonates as a cavity and these resonances need to be damped. By coupling to the electric and magnetic fields in the main cavity resonant modes near the tank wall one can introduce such damping. A resistively loaded grid structure parallel to the tank wall and connected to the electron backscatter suppression grid(s) (in front of the wall) through resistors is one way to do this. Perhaps active damping devices using feedback control from field sensors could also help damp the cavity resonances. Another important set of resonances is associated with the system under test and these resonances radiate a wave toward the cavity walls. This wave from the system will be reflected from the walls and this reflection should be minimized.

The air density in the vacuum chamber must be made small enough to simulate the resulting electron transport situation in space around an exoatmospheric system. The density need not be as small as that in space but it must be small enough that new effects are not introduced to a significant degree. The molecular density should be small enough that electrical breakdown does not occur and that no significant ionization is produced by collisions of the high energy electrons with molecules of the background gas. There is a small ambient electron density in space and for completeness one could try to simulate this effect in the test chamber as well.

There are various other features such a simulator should include. These relate to making the system function normally in the test chamber so that it is operating during the test. Such features are somewhat system specific.

This general simulator concept can be rather useful in giving quality EMP simulation for the systems generated EMP. It has been buried in my notebooks for some time. I hope to get out some notes on this type of simulator in the not too distant future. One such note was started quite some time ago but it has been interrupted by various other notes.

C. Simulators for exciting systems by the use of pulsed electron sources located on the system

A somewhat less complete simulation than that just discussed involves removing the pulsed photon source from the large vacuum chamber, calculating the electron emission from the various parts of the system structure for the given photon environment from the nuclear weapon, and producing this electron emission in amplitude, waveform, spectrum, etc. by pulsed electron sources attached directly onto the various important parts of the system structure. All the requirements on the vacuum tank structure as far as damping of resonances and other electrical characteristics still hold. The air density requirements also remain.

This type of simulator is somewhat limited in not having a photon environment present to produce the transient radiation effects on the electronic components of the system (TREES) simultaneously with the EMP environment. The use of many electron emitters will result in a rough approximation to the continuously distributed electron emission throughout the system which a photon source would have produced. There is also the practical difficulty of getting sufficiently small electron sources that can be placed on the system conductors so as to not disturb the system response characteristics by their presence.

D. Two dimensional and one dimensional simulators

A yet cruder approach toward simulating the systems generated EMP on exteriors of systems involves first calculating the electron emission from the system and the subsequent electron trajectories so as to have calculated the exterior surface current and charge densities. This involves calculating also the net current waveforms for current leaving or returning to the system exterior.

Place the system inside a conducting shell which is not necessarily a vacuum enclosure. Connect many pulsers each with its appropriate waveform between parts of the system exterior and the external conducting shell. If these pulsers are high impedance current sources then the proper current into or out of each part of the system is approximately reproduced.

Next add distributed drivers in the outer conducting shell similar to those in a one dimensional simulator (as in figure 4.10) except that they may not go around the whole surface but be local magnetic field producers. These can be used to partly control the surface current density running along the system structure.

In effect this is a two dimensional EMP simulator producing the desired surface current and charge densities on the system. It is a rather complex simulator and less desirable from the viewpoint of quality simulation. In the case of a long thin system geometry this is reduced to a one dimensional simulator which is somewhat easier to design and understand in detail.

VIII. Summary

When designing a specific EMP simulator for 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 simulator dimensions.

   a. What are the dimensions of the systems to be tested?

   b. What distortion of the system response is to be allowed (fractional 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?

   c. What distortion of the fields, currents, etc. incident on the system is to be allowed due to non ideal 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 non ideal 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 non nuclear 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.

This note should help to organize the many EMP simulator types so that one can see how they relate to one another. One can also see what are some of the general things possible for EMP simulators. This note also can indicate where some further development of the state of the art of EMP simulation technology is needed.

This note presents a mosaic of EMP simulator types. Not only is each type interesting in itself, but the pattern formed by the whole is also interesting. Both viewpoints are useful. The references cited in this note are mostly general discussions of types of EMP simulators. Specific design questions are found in numerous Sensor and Simulation Notes by other authors and myself.

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