Interaction Notes
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Electromagnetic Pulse Interaction Close to Nuclear Bursts and Associated EMP Environment Specification

Capt Carl E. Baum
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Abstract

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I. Introduction

The consideration of electromagnetic interaction with objects can be quite complex if highly accurate solutions are sought. At least in principle and often in practice one can solve Maxwell's equations with appropriate mathematical constraints such as boundary conditions and radiation condition at infinity etc., or with numerical approaches one can solve Maxwell's equations to arbitrary precision. However, one must specify various mathematical conditions into Maxwell's equations such as the constitutive relations involving permittivity and permeability, and perhaps the conductivity and other physical laws relating charge motion to other electromagnetic quantities.[1] In general one does not normally know these relationships exactly and so various approximate relationships are used. Sometimes approximate relationships of this type are used merely to simplify the mathematics. Thus for some applications one may purposely carefully choose the geometry, the materials, and any other relevant electromagnetic parameters from the point of view of having the electromagnetic characteristics of the device in question well known to high accuracy over some frequency range and/or time window of interest. Examples of such objects can include sensors for measuring electromagnetic quantities (fields, currents, etc.) or devices for producing controlled and accurately known field distributions etc. for calibration and/or other experimental purposes.

Not all electromagnetic questions of interest involve devices chosen for their accurately known electromagnetic characteristics. Often one is concerned with understanding the electromagnetic response of some structure which has been designed for some other kinds of characteristics; this typically makes the electromagnetic response more difficult to calculate. However, one can usually make rough approximations to describe the electromagnetic performance of the object. Such approximations may be adequate for the purpose at hand or may serve as a first step toward a more accurate calculation of the electromagnetic response.

In what is generally termed the interaction problem one is concerned with a quantitative understanding of the mechanisms by which the nuclear electromagnetic pulse produces currents, voltages, etc. on objects of interest such as missiles, aircraft, ships, buildings, etc. In thinking about this interaction it is useful to consider first the total system geometry as one big antenna on which currents will flow in response to the electromagnetic pulse. This consideration can be refined to second take account of some of the details of the system geometry such as deliberate antennas, apertures, distribution of current in

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[1] Rationalized MKSA units are used throughout.

cabling, etc. so as to understand the response characteristics of these parts of the system in an environment which includes not only the incident electromagnetic pulse (defined in some appropriate sense) but also the electromagnetic environment produced in the vicinity of the part of the system being considered by the presence of the total system geometry in the incident electromagnetic pulse.

In trying to quantitatively understand the system interaction with the EMP it is useful to have some simple models that approximately describe the principal interaction mechanisms. Such mathematical models can be used to quickly estimate the magnitude of the electromagnetic coupling. Furthermore such models give one some insight into how to divide up the system interaction problem into various appropriate subproblems.

In considering the system interaction one must have some knowledge of the EMP environment. But just what is this environment? There are lots of parameters one might call the EMP environment. But will just any old parameters suffice? Clearly those features of the electromagnetic environment which are directly related to the response of the various kinds of systems of interest should be included in any general specification of the EMP environment. This brings one back to the simple interaction models for describing some of the principal interaction mechanisms; such approximate mathematical models directly include various parameters of the EMP environment and these parameters should then be included in environment specifications.

In many cases one is concerned with electromagnetic interaction in a medium where there are no sources and no conductivity; this medium can also typically be characterized as free space. Much work has been done in solving electromagnetic boundary value problems relating to electromagnetic interaction with systems for such cases, typically using some kind of plane wave excitation. For such free space questions one can obtain much detailed information regarding interaction modes such as resonances, aperture penetrations, shielding, etc. The results may be functions of polarization, angle of incidence, pulse width, etc. However, one should not think that these detailed characteristics carry over exactly to all interaction problems of interest. Specifically there are many cases when the system is in a conducting medium, such as in the earth for example. As another example this conducting medium may be ionized air in the nuclear source region so that the conductivity is rapidly changing as a function of time; the medium is also nonlinear because the electron mobility is a function of the electric field. Furthermore there is a large compton current density in the medium. The nuclear source region is quite different from the case of free space with say plane wave incidence.

Not only are the electromagnetic parameters in the nuclear source region different from those in free space in the sense of what is there in the absence of the system. In addition the interaction of the system or object of interest with this electromagnetic distribution is in general different. If one is to understand interaction in a nuclear source region then one should go back to electromagnetic fundamentals and include all the essential electromagnetic characteristics of the medium.

Starting from electromagnetic fundamentals one can derive simple models for electromagnetic interaction applying to the nuclear source region as well as free space. Specifically we consider the low frequency limiting forms of interaction with simple objects which are basically the electric and magnetic dipole types of interaction. This requires that skin depths or radian wavelengths be larger than the object and so this type of model does not apply for all frequencies. However it can typically apply over a large band of frequencies of interest.

In this note we start from Maxwell's equations and other related equations and identify various terms that naturally come out of these equations. Then looking at the simple dipole interaction models the various relevant terms are identified here as well and are found to correspond with those identified in Maxwell's equations. These features then form a basis for categorizing the environment. Such a categorization does not solve all the kinds of questions one may ask with regard to interaction in a nuclear source region. However, it is a start and provides a rational basis for thinking about such a complex environment.

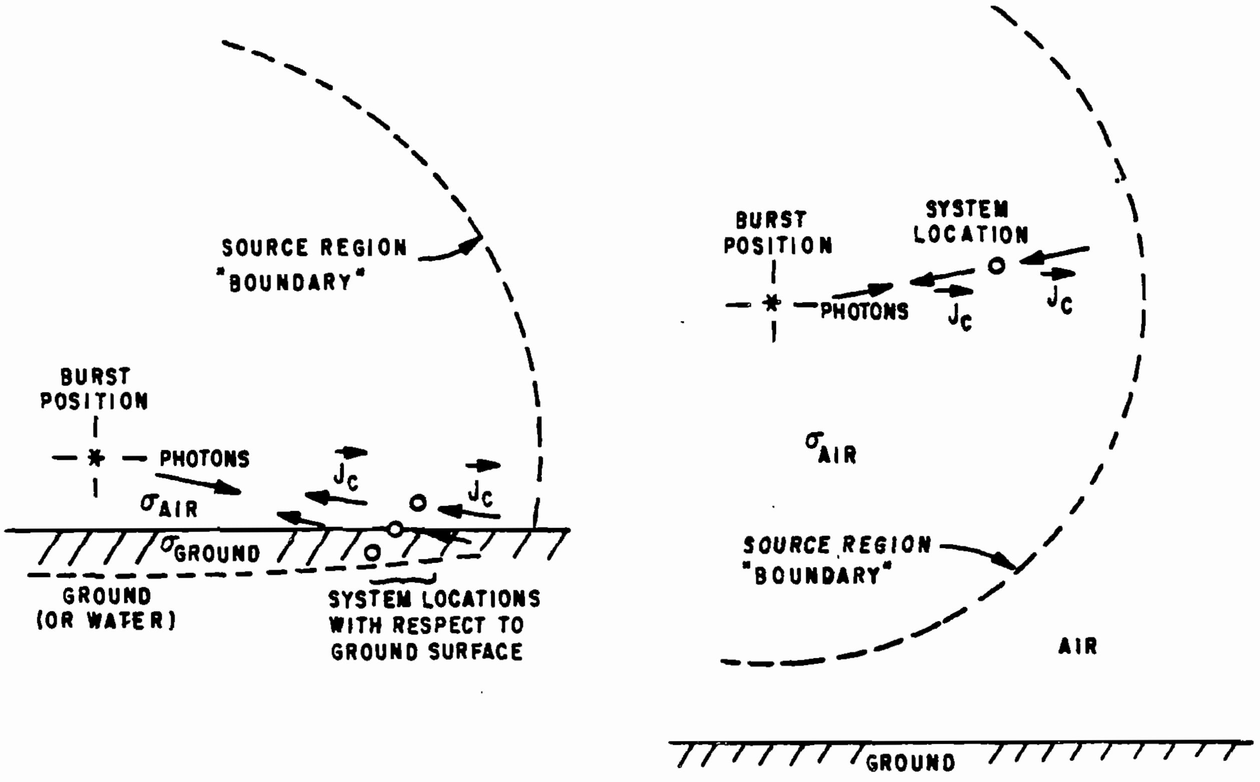
The dipole model is limited in a few respects. For the electric dipole the medium nonlinearities are not completely included in the linear equivalent circuit and this introduces some errors, but the results are still very approximately correct and give the trend of things. Furthermore the dipole model is a low frequency model and the highest frequency for which the model is valid depends on the object size and the medium conductivity. This limited range of validity is offset on the other hand by the simplicity and generality of the results.

Having a first order view of the environment and its associated interaction with objects of interest one can then go on to consider other cases, basically those involving electrically large objects. Some general forms of such objects can be profitably considered because of their applicability to many real objects of interest; some of these are pointed out. Thus based on a consideration of the physics of the environment and its interaction with objects one can formulate a set of quantities which are needed for an environment specification, particularly as it applies to the nuclear source region. Combining this approach with some detailed solutions of interaction problems at high frequencies and/or including nonlinearities applying to typical geometries of interest in nuclear source regions one can get a somewhat comprehensive view of EMP interaction in nuclear source regions.

II. Important Quantities as Viewed from the EMP Environment in a Nuclear Source Region

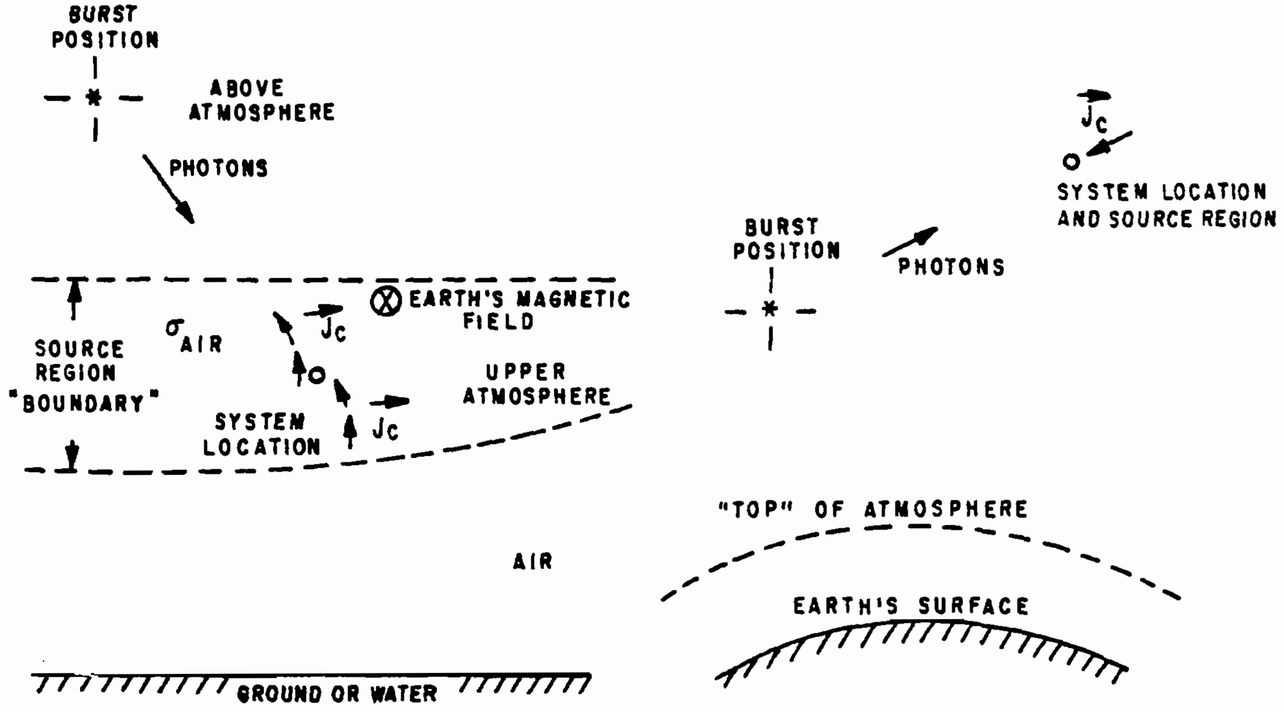
The nuclear source region for the electromagnetic pulse has some important electromagnetic properties which are quite different from those outside the source region. In the source region there is a source current density of high energy electrons which are produced from high energy photons (γ rays, X rays) for the most part through the compton scatter process and to some extent by the photoelectric and pair production processes in the air or any other material that happens to be present. There is also a time changing air conductivity which is a function also of the local electric field making the problem nonlinear. This conductivity comes about because the high energy electrons ionize the air in the process of slowing down. Not only does the air become conducting. The soil, rock, etc. can have their conductivities changed (and in principle their permittivities as well) and various nonconducting objects (dielectric insulators, etc.) that are of concern as parts of systems of interest can be made somewhat conducting as well. The nuclear source region is then quite different from an ordinary situation involving electromagnetic interaction and scattering. There can be direct deposition of charge on objects because of the compton current density and the air conductivity allows conduction currents to flow onto objects. These additional processes are an essential part of the nuclear EMP environment in the nuclear source region and as such should be an essential part of the environment description and specification.

EMP source regions come in several different geometries depending on the relative positions of the bomb, the atmosphere, the ground or water surface, and the object (or system) with which the EMP interaction is being considered. Figure 1 shows several cases of EMP source regions that one can consider. Figure 1A shows the case of a near surface burst with a source region which is roughly hemispherical above the ground but which also penetrates into the ground somewhat because of the non zero mean free path of the high energy photons in the ground. This case also applies to a nuclear burst over water as well as ground. A system required to survive in this environment might be located above, at, or below the ground surface, Typical systems of interest for this case would be near the ground surface, perhaps partly above and partly below. Examples of such systems might include missile launch facilities and command, control, and communication (C^3) centers which are somewhat mechanically hardened. Figure 1B shows the case of an air burst with a



A. NEAR SURFACE BURST (OR GROUND BURST) INTERACTION

B. INTERMEDIATE ALTITUDE (OR AIR BURST) INTERACTION



C. HIGH ALTITUDE BURST INTERACTION FOR SYSTEM IN UPPER ATMOSPHERE

D. EXOATMOSPHERIC BURST INTERACTION FOR SYSTEM ABOVE ATMOSPHERE

FIGURE 1. SOME NUCLEAR WEAPON AND SYSTEM GEOMETRIES FOR EMP INTERACTION WITH THE SYSTEM IN THE NUCLEAR SOURCE REGION

roughly spherical source region which does not reach to the ground. An example of a system in such a source region might be a reentry vehicle under attack by an interceptor missile. Figure 1C shows the case of what is commonly termed a high altitude burst where the nuclear source region of interest is in the upper atmosphere below the burst altitude. The source region geometry is shaped something like an oblate spheriod but somewhat distorted. In this type of nuclear source region the earth's magnetic field plays a significant role in turning the current density ($\vec{J}_C$) of high energy electrons, making for a large radiated pulse below the source region. Inside this kind of source region one might be considering systems such as missiles being launched upwards or reentry vehicles coming down into the atmosphere.

In Figure 1D we have the case with both the nuclear burst and system of interest outside of the atmosphere and with no significant atmosphere or other matter intervening between the two. With no significant atmosphere around the system the EMP generation here is quite different from the more "classical" cases such as shown in figures 1A through 1C. Here the high energy electrons are produced only by the direct interaction of the high energy photons with the system itself. These high energy electrons knocked off the system generate fields outside the system and make currents flow on the system in a rather complicated situation depending on the details of the system geometry, spectrum of the emitted electrons, etc. An example of a system where such source region consideration is appropriate is a satellite. This external system-generated EMP is quite different from the case in an atmospheric source region because of the absence of the air conductivity and the inclusion of a complicated electron dynamics problem for the electron cloud around the system acting under the influence of the EMP fields. This type of EMP situation is similar in some respects to what is termed the internal EMP. In both cases the presence of the system is fundamental to the generation of the EMP. One might call these cases by a common name of system generated EMP, either external or internal for the two cases separately. The considerations in this note have some bearing on the system generated EMP. However beyond the incident photon flux, things like the fields cannot be specified in the sense of an incident environment because they are generated by the system geometry and as such vary from system to system. For such cases the incident nuclear radiation is the environment to be specified.

In this note we concentrate on the general characteristics of the EMP environment as generated in the atmosphere and applying to the cases shown in figures 1A, 1B, and 1C. This environment is to be something produced in the absence of the system, but which directly applies to the interaction of the EMP with the system. For the case of system generated EMP the presence of the system is essential for the generation of any EMP of interest. This applies to any internal EMP as well as the example in figure 1D. While an incident EMP environment does not apply for such cases of system generated EMP, still some of the concepts discussed here for source region interaction apply to system generated EMP. The amount of current knocked off an exoatmospheric system is related to its area and various parts of the system can be viewed as electric and magnetic dipoles which respond in the electromagnetic environment generated by the photon interaction with the total system geometry. Of course there is not an air conductivity but some kind of electron cloud in the absence of an ambient air medium and this considerably complicates the interaction problem as far as describing the properties of the medium in which the various parts of the system are immersed. In this note the medium is simply viewed as a conducting dielectric which does not apply to some of the system generated EMP questions.

Having considered some examples of source region geometries let us briefly consider what is meant by the EMP source region in the atmosphere, soil, etc. (in the absence of the system). This is defined as that place where the nuclear radiation induced source current density $\vec{J}_c$ and/or conductivity or conductivity increase is significant. To quantify the meaning of significant one can compare these quantities to other electromagnetic quantities which are present for their relative magnitudes. The source current density $\vec{J}_c$ can be compared to the displacement current density $\partial\vec{D}/\partial t$ or a conduction current density $\sigma\vec{E}$ for a non radiation induced conductivity as in the case of soil or sea water. The nuclear induced conductivity can be considered in the conduction current density $\sigma\vec{E}$ as in the air and compared to the associated displacement current density $\partial\vec{D}/\partial t$. Where equality between the compared quantities approximately holds can be considered as the source region boundary, generally a rather indistinct boundary. This is further complicated by the fact that the various electromagnetic quantities have various time histories, or if one prefers various Fourier transforms. Thus one might compare peak values, rise time, pulse widths, etc. in the time domain and/or characteristics of the Fourier transformed waveforms over various frequency bands. The EMP source region is then only a rough concept, but one which has use in identifying the presence of some additional distinctive features of the environment. Note that the nuclear radiation induced $\vec{J}_c$ and σ are additional features of the environment. So a general consideration of the EMP environment can also be structured so as to include the case that the nuclear radiation induced quantities $\vec{J}_c$ and σ are negligible as a subset of the more general problem.

In considering the EMP source region environment the starting point is of course Maxwell's equations which we write in the form

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \equiv -\vec{w}$$
$$\nabla \times \vec{H} = \vec{J}_t \tag{1}$$

where $\vec{J}_t$ is the total current density defined as

$$\vec{J}_t \equiv \vec{J} + \frac{\partial \vec{D}}{\partial t} \tag{2}$$

where the displacement current density is

$$\vec{J}_d \equiv \frac{\partial \vec{D}}{\partial t} \tag{3}$$

having units of amps/meter^2. For an EMP source region the current density $\vec{J}$ is conveniently split into two terms as

$$\vec{J} = \vec{J}_c + \sigma \vec{E} \tag{4}$$

where $\vec{J}_c$ is often called the compton current density but is more generally the current density of high energy electrons produced by any process from the nuclear radiation. Another term introduced is the conductivity σ which in the case of the air is produced by the ionization associated with the slowing down of the high energy electrons. For some media such as soil the conductivity is already present but may be altered by the high energy electrons. The conductivity is further complicated by being a function of the electric field (at least in air) making the problem nonlinear. Furthermore the conductivity can be somewhat anisotropic as in the case of the ionosphere giving σ matrix characteristics. The conduction current density is

$$\vec{J}_\sigma \equiv \sigma \vec{E} \tag{5}$$

which is referred to as Ohm's law. For convenience we define

$$\vec{J}_e \equiv \vec{J}_\sigma + \frac{\partial \vec{D}}{\partial t} \tag{6}$$

This is the current density which flows in response to the electric field and which together with the source current density $\vec{J}_c$ gives the total current density as

$$\vec{J}_t = \vec{J}_c + \vec{J}_e \tag{7}$$

Besides Maxwell's equations and Ohm's law we need the constitutive relations

$$\begin{aligned} \vec{D} &= \varepsilon\vec{E} \\ \vec{B} &= \mu\vec{H} \end{aligned} \tag{8}$$

Typically the permeability μ is approximately μ_o, the permeability of free space. The permittivity ε may be approximately the permittivity of free space ε_o as in the case of sea-level air, even though ionized, because of the very large collision frequency of the conduction electrons. However, in soil the permittivity will differ from that of free space, and in the ionosphere the plasma there also alters the permittivity making it somewhat anisotropic with matrix properties. Of course any change in ε away from ε_o is associated with charge motion in the medium and it is only a matter of convenience whether one includes this current density in ε in the displacement current density or in σ in the conduction current density. Rewriting equations 5, 6, and 8 for an assumed time independent scalar ε we have

$$\vec{J}_e = \left(\sigma + \varepsilon \frac{\partial}{\partial t}\right)\vec{E} \tag{9}$$

showing the somewhat interchangeable roles of σ and ε in relating $\vec{E}$ to $\vec{J}_e$. For simplicity the forms of σ and ε as in equation 9 (and similarly for the permeability μ) will be retained throughout this note. Note, however, that σ, ε, and μ can have more general forms which alter the forms of some of the equations somewhat, but do not alter the basic discussion in this note.

One of the source parameters, the source current density $\vec{J}_c$, comes directly from the nuclear radiation and is basically the source term in Maxwell's equations. In some cases, however, it is also affected by the EMP fields making the source term somewhat nonlinear. On the other hand while the nuclear radiation induced conductivity is generated from the radiation source it also decays so that in the case of air a set of differential equations (the "air chemistry" equations) is used to describe the densities of charge carriers typically as

$$\frac{\partial n}{\partial t} = S_e - \nu_a n - \alpha_r N_+ n$$

$$\frac{\partial N_+}{\partial t} = S_e - \alpha_r n N_+ - \alpha_i N_- N_+ \qquad (10)$$

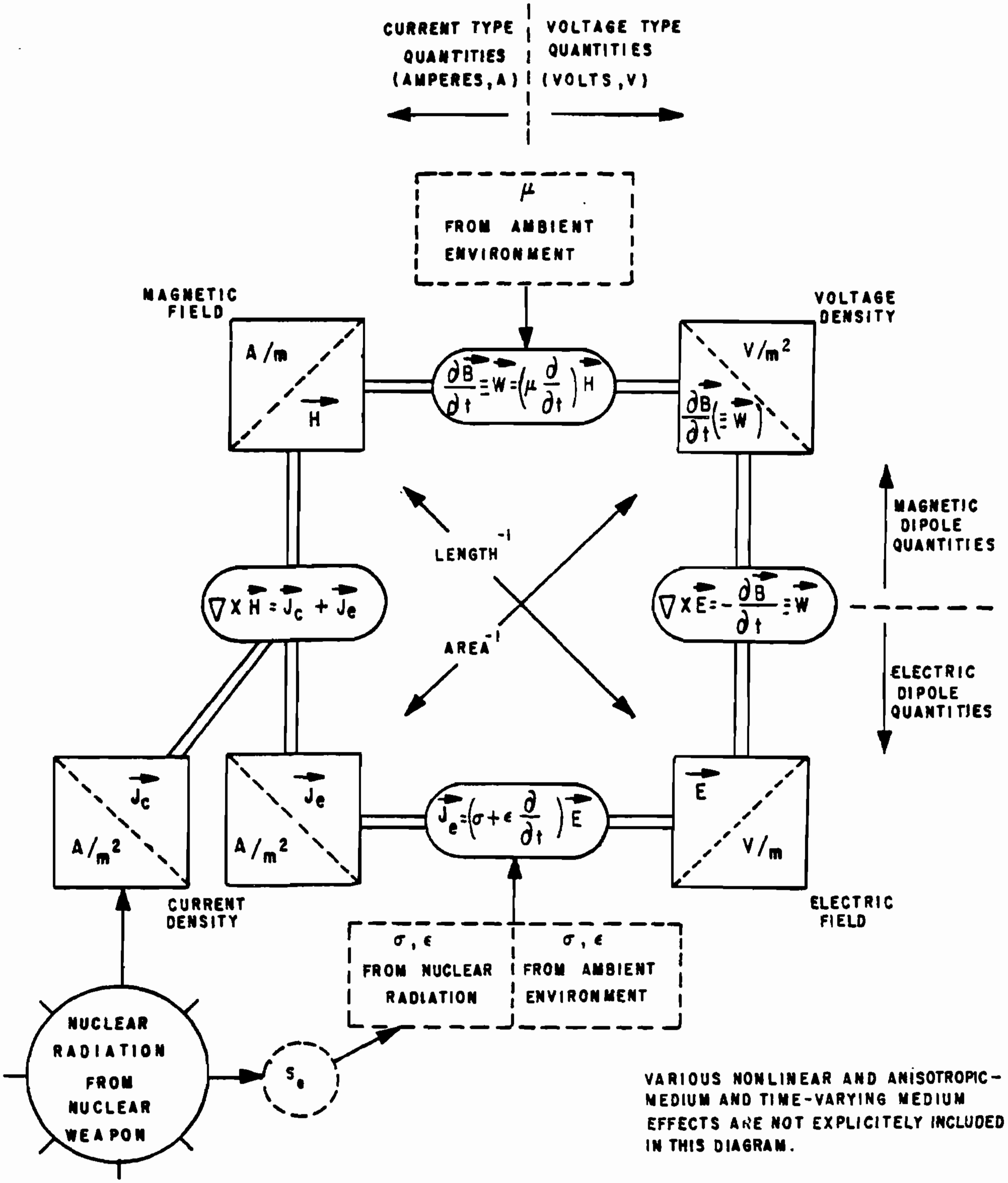
$$n + N_- = N_+$$

which relate the electron density n, position ion density N_+, and negative ion density N_-. The nuclear radiation source in these equations is S_e (meter^{-3}s^{-1}) giving the temporal and spatial generation rate for electron-ion pairs. The electron attachment rate to neutral oxygen molecules ν_a (about 10^8 s^{-1} at sea level) is an important loss term for the electron density. Also included in equations 10 are an electron-ion recombination coefficient α_r and an ion-ion recombination coefficient α_i. Equations 10 are only approximate and are a gross simplification of the atomic physics processes occurring in ionized air. Nevertheless they do point out the term S_e which represents the nuclear radiation input to the air conductivity. To find the air conductivity one uses

$$\sigma = e[\mu_e n + \mu_+ N_+ + \mu_- N_-] \qquad (11)$$

where e is the magnitude of the electron charge and the subscripted μs are the mobilities of the corresponding charge carriers. Since the electron mobility μ_e is a strong function of the electric field magnitude for electric fields of interest then the air conductivity introduces a significant nonlinearity into Maxwell's equations in the source region. Note that equation 11 is not strictly accurate in some cases such as at high altitudes where the charge carrier motion can be significantly affected by the earth's magnetic field and the EMP fields introducing both matrix and nonlinear characteristics into the mobilities and thus into the air conductivity. Again note that σ and ε can both be considered as being affected by the presence of electron and ion densities; σ and ε can then be considered together as being altered by the nuclear ionization rate S_e so that S_e can be thought of as the source term for the relation (generally nonlinear) between $\vec{J}_e$ and $\vec{E}$ as in equation 9 or more general relation replacing it.

Now let's start to form some general picture of the basic quantities of the EMP environment. This picture, at a minimum, includes Maxwell's equations, the electromagnetic properties of the media of interest as contained in the constitutive relations and Ohm's law, and the nuclear source terms as in the source current density and in the ionization rate and the resulting conductivity and permittivity. These quantities and their interrelationships are represented in a diagram in figure 2. There are four basic types of electromagnetic quantities in this



VARIOUS NONLINEAR AND ANISOTROPIC-MEDIUM AND TIME-VARYING MEDIUM EFFECTS ARE NOT EXPLICITELY INCLUDED IN THIS DIAGRAM.

FIGURE 2. DIAGRAM OF THE BASIC ELECTROMAGNETIC QUANTITIES FOR SOURCE REGION EMP ENVIRONMENT AND INTERACTION

diagram linked together by four equations: two Maxwell equations and two constitutive equations (with σ included with ε in one equation). The four basic electromagnetic quantities have units formed by taking one of the two quantities volts and amperes and combining them by multiplication with one of the two quantities meter^{-1} and meter^{-2}. These four electromagnetic quantities are directly related to the electrical circuit quantities voltage and current, but on a per unit length or per unit area basis as is appropriate for distributed electromagnetic field quantities. This units feature is significant because in considering the lowest order interaction mechanisms in the next section these four quantities are the quantities intercepted by electric and magnetic dipoles for their open circuit voltage or short circuit current.

The four basic electromagnetic quantities are first a total current density $\vec{J}_t$ which for an EMP source region has a source current density $\vec{J}_c$ and an electric-field-associated current density $\vec{J}_e$, second a magnetic field $\vec{H}$, third a time rate of change of a magnetic field (or magnetic flux density) $\partial\vec{B}/\partial t$ which might be called a voltage density and given its own symbol, say $\vec{W}$ (units V/m^2 (the same as T/s) in direct analogy to current density), and fourth an electric field $\vec{E}$. Together these four quantities form what might be called the electromagnetic cycle. Each of the terms is related to its two nearest neighbors in the cycle by an equation (a Maxwell equation in one case and a constitutive equation in the other). In many circumstances this cycle is self sustaining as, for example, in the case of electromagnetic wave propagation in free space. In an EMP source region, however, the conductivity makes the medium absorb electromagnetic energy. On the other hand this is offset by the generation of electromagnetic energy associated with the source current density.

Thus our electromagnetic cycle is connected to the nuclear radiation at two positions around the cycle, introducing a source term as well as loss into the cycle. As shown in figure 2 the source current density enters the cycle at the same place as $\vec{J}_e$ but only appears in one of the equations with $\vec{J}_e$. This is somewhat nonsymmetric but this difference is important in differentiating $\vec{J}_e$ and $\vec{J}_c$ as separate parts of $\vec{J}_t$, each with its own important features. Another nonsymmetric feature is the introduction of radiation induced conductivity in one of the constitutive equations without introducing a comparable magnetic conductivity term in the other constitutive equation. This asymmetry is due to the lack of known magnetic charge and associated magnetic current in the material universe. The permeability μ can have an energy loss characteristic (as in hysteresis for example) but μ is still associated with the motion of electric charge. For present purposes, as in the diagram in figure 2, the permeability is assumed a simple scalar which can be moved through the time derivative, just like ε. Note that charge motion is affected by both electric and magnetic fields as in the Lorentz force law

$$\vec{F} = q[\vec{E} + \vec{v} \times \vec{B}] \tag{12}$$

where $\vec{F}$ is the force on the charged particle, q is the charge, and $\vec{v}$ is the particle velocity.

Note in figure 2 that the nonlinearities are not indicated. The source current density, conductivity, and permittivity are all functions of the electric and magnetic fields unless these fields are sufficiently small. For typical cases of interest for EMP source regions the air conductivity is a strong function of the electric field. For high altitude source regions the source current density is a strong function of the magnetic field, particularly the ambient earth's magnetic field. For quite close in positions in the EMP source region where $\vec{J}_c$ and S_e get quite large then all the nonlinear effects of the electric and magnetic fields on both $\vec{J}_c$ and σ become important. These nonlinear processes can be represented in the diagram in figure 2 by linking $\vec{H}$ and $\vec{E}$ to $\vec{J}_c$ and σ and thereby complicating the diagram somewhat. In any case we have identified five electromagnetic field types of terms: $\vec{J}_c$, $\vec{J}_e$, $\vec{H}$, $\partial\vec{B}/\partial t = \vec{W}$, and $\vec{E}$ as primary electromagnetic quantities to be included in a source region environment description. In addition to these there are the secondary electromagnetic parameters: σ and ϵ together with their source S_e as being important EMP environment quantities. The permeability μ is of course important but it is normally the permeability of free space μ_o, at least approximately, and so it is not too interesting. Also the permittivity ϵ of air in some cases is just ϵ_o approximately with the ionization being included under σ. However in other cases both for air and other media such as soil it is convenient to consider ϵ as a variable quantity in some appropriate sense.

The basic electromagnetic quantities ($\vec{H}$, $\partial\vec{B}/\partial t = \vec{W}$, $\vec{E}$, and $\vec{J}_t$ which splits into $\vec{J}_c$ and $\vec{J}_e$) follow quite naturally from Maxwell's equations together with the constitutive equations which incorporate the medium parameters (μ, σ, and ϵ or other more detailed forms relating charge motion in the presence of magnetic and electric fields). This same basic division of the electromagnetic vector field type quantities also appears in other general aspects of the electromagnetic equations. Consider the integral form of Maxwell's equations. These are found from equations 1 by integrating over an appropriate surface; then converting the surface integral of a curl to a line integral gives

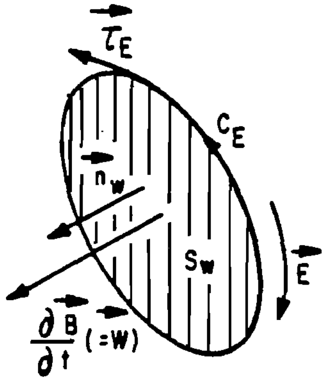
$$\oint_{C_E} \vec{E} \cdot \vec{\tau}_E ds_E = -\iint_{S_W} \frac{\partial \vec{B}}{\partial t} \cdot \vec{n}_W dS_W = -\iint_{S_W} \vec{W} \cdot \vec{n}_W dS_W$$

$$\oint_{C_H} \vec{H} \cdot \vec{\tau}_H ds_H = \iint_{S_J} \vec{J}_t \cdot \vec{n}_J dS_J \tag{13}$$

The incremental contour length is ds with a unit tangent vector $\vec{\tau}$, the incremental surface area is dS, and the unit surface normal vector is $\vec{n}$. The choice of the reference side of the surface for $\vec{n}$ to point away from and reference direction $\vec{\tau}$ along the contour describing the edge of the surface form the basis of what is termed the right hand rule in electromagnetics. The symbols for contour C and surface S as well as line element, incremental area, unit normal vector, and unit tangent vector are all subscripted to indicate the electromagnetic quantity with which they are each associated.

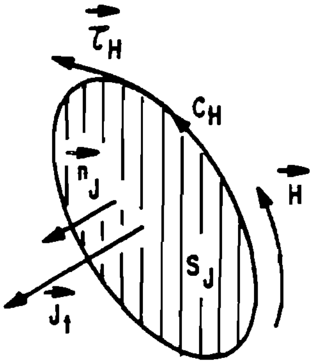
Referring to figure 3 the surfaces and contours show some general features of the Maxwell equations. Figure 3A shows the relation of $\partial\vec{B}/\partial t$ (or $\vec{W}$) through a surface to $\vec{E}$ around a contour forming the edge of this surface. Figure 3B shows the relation of $\vec{J}_t$ through a surface to $\vec{H}$ around the edge contour. Note that of these four quantities those two with a factor meter^{-1} in their units are associated with contour integrals and the remaining two with a factor meter^{-2} in their units are associated with surface integrals. This sheds some light on the pattern of the units of the basic electromagnetic quantities as arrayed in the diagram in figure 2. Going on to figure 3B the four quantities $\vec{J}_t$, $\vec{E}$, $\partial\vec{B}/\partial t = \vec{W}$, and $\vec{H}$ are included in a simple diagram which includes the contours C_E and C_H and the surfaces S_W and S_J for the simple case of $\partial\vec{B}/\partial t$ shown parallel to $\vec{H}$ and $\vec{J}_t$ antiparallel to $\vec{E}$. The two terms in each of these pairs are not necessarily parallel to each other as illustrated in figure 3B because of the time derivatives and possible matrix characteristics of σ, ε, and μ appearing in the constitutive equations relating $\vec{J}_e$ to $\vec{E}$ and $\partial\vec{B}/\partial t$ to $\vec{H}$. Furthermore if the source current density $\vec{J}_c$ is nonzero it could also make $\vec{J}_t$ not parallel to $\vec{E}$. However some types of electromagnetic waves (a free space plane wave of linear polarization away from sources, for example) do have the terms in each pair parallel (or antiparallel) to one another. An interesting feature of the simple diagram in figure 3B is that it illustrates the tight interrelationship that exists among the four basic electromagnetic field types of quantities.

The four basic quantities $\vec{H}$, $\vec{J}_t$, $\vec{E}$, and $\partial\vec{B}/\partial t$ also appear in the boundary conditions at a surface separating two media. These boundary conditions can be simply derived from the integral



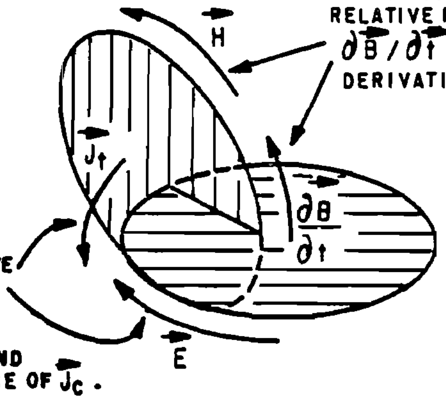
$$\oint \vec{E}\cdot\vec{\tau}_E \, ds_E = -\iint \frac{\partial \vec{B}}{\partial t}\cdot \vec{n}_w \, dS_w$$

A. ELECTRIC FIELD WITH VOLTAGE DENSITY



$$\oint \vec{H}\cdot\vec{\tau}_H \, ds_H = \iint_{S_J} \vec{J}_t\cdot \vec{n}_J \, dS_J$$

B. MAGNETIC FIELD WITH TOTAL CURRENT DENSITY



THIS IS NOT IN GENERAL THE RELATIVE POLARITY OF $\vec{H}$ AND $\partial \vec{B}/\partial t$ DUE TO THE TIME DERIVATIVE.

FOR ILLUSTRATION $\vec{H}$ IS CHOSEN PARALLEL TO $\partial \vec{B}/\partial t$ AND $\vec{J}_t$ IS CHOSEN ANTIPARALLEL TO $\vec{E}$.

THIS IS NOT IN GENERAL THE RELATIVE POLARITY OF $\vec{J}_t$ AND $\vec{E}$ DUE TO THE TIME DERIVATIVE TERM AND POSSIBLE PRESENCE OF $\vec{J}_c$.

C. FOUR BASIC QUANTITIES $\vec{J}_t$, $\vec{H}$, $\partial \vec{B}/\partial t$, AND $\vec{E}$

FIGURE 3. SURFACES AND CONTOURS FOR INTEGRAL FORM OF MAXWELL'S EQUATIONS

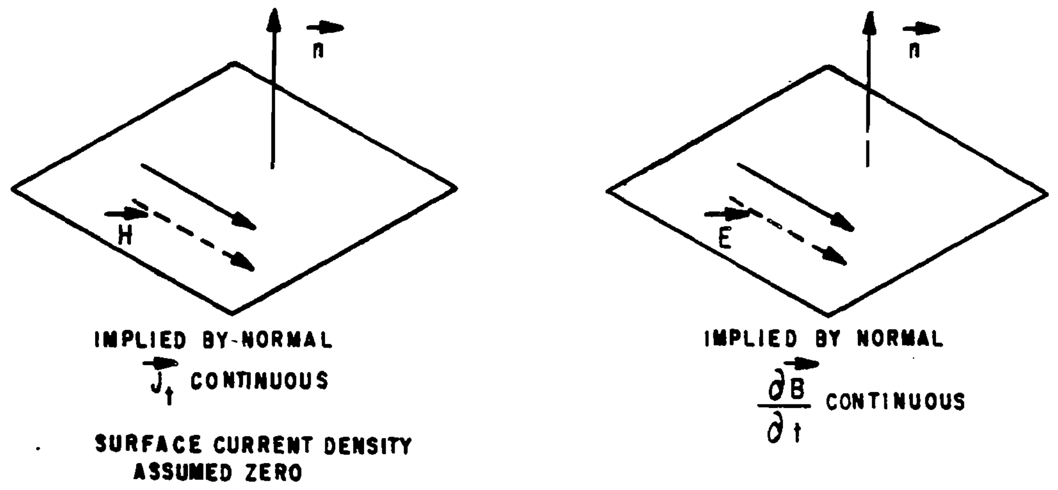
form of Maxwell's equations as in equations 13. These are the standard boundary conditions relating to the continuity of tangential or normal components of appropriate vector quantities through the surface. Figure 4A shows $\vec{H}$ and $\vec{E}$ as parallel to surfaces to illustrate the continuity of the tangential components of these fields through the surface. This can be expressed in terms of the unit normal vector $\vec{n}$ for the surface of interest as the requirement that $\vec{n} \times \vec{E}$ and $\vec{n} \times \vec{H}$ be continuous through the surface. Figure 4B shows $\vec{J}_t$ and $\partial\vec{B}/\partial t$ as perpendicular to surfaces to illustrate the continuity of the normal components of these vector quantities through the surface. Said in another way $\vec{n} \cdot \vec{J}_t$ and $\vec{n} \cdot \partial\vec{B}/\partial t$ are continuous through surfaces. Taking the divergence of Maxwell's equations (equations 1) gives

$$\nabla \cdot \left(\frac{\partial \vec{B}}{\partial t}\right) = \nabla \cdot \vec{W} = 0$$

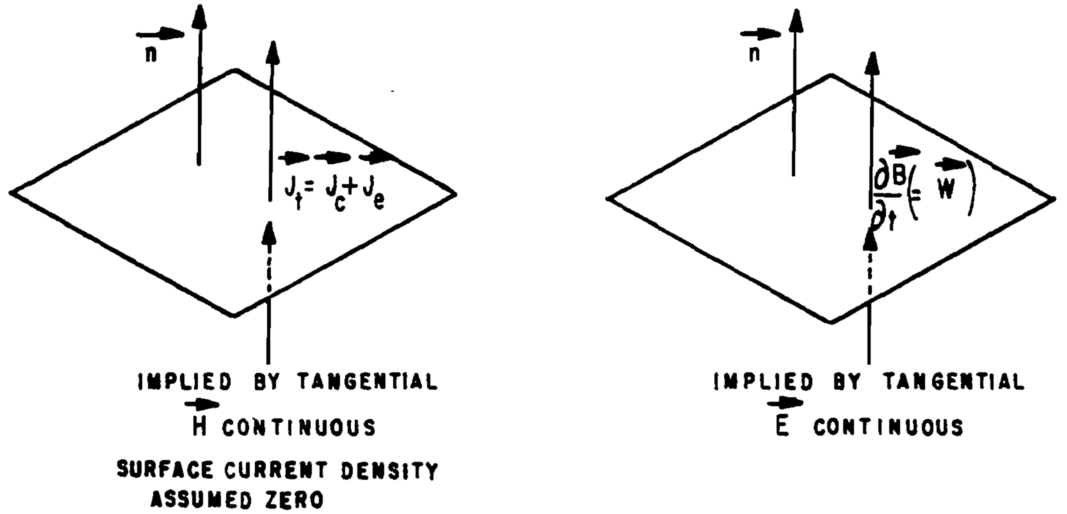
$$\nabla \cdot \vec{J}_t = \nabla \cdot \vec{J} + \nabla \cdot \left(\frac{\partial \vec{D}}{\partial t}\right) = \nabla \cdot \vec{J} + \frac{\partial \rho}{\partial t} = 0 \tag{14}$$

so that both $\vec{J}_t$ and $\partial\vec{B}/\partial t$ are solenoidal vector quantities implying the continuity of their normal components through surfaces. Relating surface integrals of the normal components of $\vec{J}_t$ and $\partial\vec{B}/\partial t$ to line integrals of $\vec{H}$ and $\vec{E}$ respectively tangential to the same surfaces through the integral form of Maxwell's equations (equations 13) shows that the boundary conditions for tangential components of $\vec{H}$ and $\vec{E}$ are tied together with the boundary conditions for normal components of $\vec{J}_t$ and $\partial\vec{B}/\partial t$ respectively. We have assumed that the surfaces are not of an ideal type which allow surface current density to flow. Such a surface can have normal $\vec{J}_t$ and tangential $\vec{H}$ discontinuous through the surface in a manner related to the surface current density.

Maxwell's equations in their integral form and the associated boundary conditions at surfaces can be used to simply interpret how currents and voltages are induced on some simple geometries. One can integrate $\vec{J}_t$ over some area to obtain a current flowing through that area and thereby intercepted by an object in its path. As in the case of a loop the voltage density $\partial\vec{B}/\partial t$ can also be integrated over an area to give a voltage at some appropriate terminals. By considering line integrals one can obtain a voltage from $\vec{E}$ and a current from $\vec{H}$ which is also interpretable in terms of the surface current density on a highly conducting surface. Areas and lengths are certainly characteristics of objects of interest in an electromagnetic environment such as in an EMP source region. As a first order estimate of the currents and voltages produced in systems then one would like to characterize a system in terms of its appropriate lengths and areas and which of the quantities $\vec{J}_t$, $\vec{H}$, $\partial\vec{B}/\partial t$, and $\vec{E}$ one combines with each area and length to obtain the currents and voltages of interest.



A. TANGENTIAL COMPONENTS OF $\vec{E}$ AND $\vec{H}$ CONTINUOUS THROUGH SURFACE



B. NORMAL COMPONENTS OF $\vec{J}_t$ AND $\partial \vec{B}/\partial t$ CONTINUOUS THROUGH SURFACE

FIGURE 4. BOUNDARY CONDITIONS AT SURFACES FOR EACH OF THE FOUR BASIC QUANTITIES OF THE ELECTROMAGNETIC CYCLE

The radiation driven source current density $\vec{J}_c$ exists in the object of interest as well as in the surrounding medium and can have different values in these different places, thereby making some net current of interest increased or decreased by the source current density in the object. Thus $\vec{J}_c$ needs separate and special treatment. An environment specification then needs the primary quantities $\vec{J}_c$, $\vec{J}_e$, $\vec{H}$, $\partial\vec{B}/\partial t$, and $\vec{E}$ expressed in terms of all their important features which might include peak amplitudes, rise times, pulse widths, etc. in the time domain as well as amplitudes of their Fourier transforms over various bands of frequencies. In addition to these primary quantities there are other important supporting quantities such as the conductivity σ of air, ground, etc. in the nuclear radiation environment because of the important role the conductivity plays in the detailed interaction of the primary quantities with objects of interest in the source region. Included with σ one should have any significant changes in the permittivity ε associated with the nuclear source region environment. As an important source for the conductivity of the air etc. one should also specify S_e, the basic generation term from the nuclear radiation term. This source term S_e can also be applied to objects of interest if parts of these objects (such as insulators) can be made significantly conducting by the presence of the nuclear radiation. However the S_e and $\vec{J}_c$ in any object are somewhat a function of the object materials and nuclear radiation spectrum and direction. Thus for more detailed understanding of the conductivity and source currents in objects of interest more detailed nuclear radiation information is required.

III. Electromagnetic Quantities as Viewed from Some Important Interaction Mechanisms

Thus far we have considered the important features of the source region EMP environment as presented by the source mechanisms and the electromagnetic equations (Maxwell's equations and constitutive equations) governing the relations among the basic quantities. In this section let us consider important features of the environment from the point of view of some of the simple and important interaction mechanisms for interaction of the EMP with objects of interest. From a consideration of these basic interaction mechanisms some electromagnetic quantities can be seen to be important. Such quantities should be included in an EMP environment specification so as to make the description of the phenomenology directly applicable to at least a first order estimate of simple electrical parameters such as currents and voltages on objects of interest.

In order to characterize the environment for interaction purposes one can consider some of the lowest order ways the electromagnetic quantities can couple to material objects. One might, for example, ask how charged particles are affected by electromagnetic fields, leading to the Lorentz force law in equation 12 as a means characterizing the important electromagnetic quantities. However one is generally concerned about more macroscopic objects involving conductors, insulators, etc. and what are the currents and voltages appearing at some positions on the object which one might think of as a terminal from which the signal can be transported via cable or some other means to other parts of the system. Using the Lorentz force law may be important in determining the electron transport associated with the effects of the fields on the source current density. For interaction purposes, however, other concepts more explicitly related to antenna response are more appropriate, even though such antenna type parameters can be mathematically related back to such equations involving average forces on electrons. We would like the antenna parameters to just be simple sensitivity numbers relating current and/or voltage from the "antenna" to the appropriate electromagnetic quantities in the EMP environment. Note the use of the word "antenna" here refers not only to deliberate communication or radar antennas which are part of a site or object of interest; it applies to any part of the site or object which has a current or voltage of interest in direct response to the EMP environment.

An important class of EMP interaction problems consists of objects which can be considered electrically small for a significant portion of the frequencies of interest. By electrically small we require that radian wavelengths

$$\lambda\!\!\!^{-} = \frac{1}{\omega\sqrt{\mu\varepsilon}} \tag{15}$$

or skin depths

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \tag{16}$$

as appropriate in the media of interest (such as the EMP source region) be large compared to the dimensions of the object for which one is estimating the "terminal" current and voltage. With ω as the radian frequency and $s = i\omega$ used for the Laplace transform variable we have the propagation constant in the forms

$$\begin{aligned} \gamma &= [s\mu(\sigma + s\varepsilon)]^{1/2} = ik \\ k &= [\omega\mu(-i\sigma + \omega\varepsilon)]^{1/2} \end{aligned} \tag{17}$$

For d as the typical dimension of the object then we require for frequencies of interest that

$$|k| << \frac{1}{d} \tag{18}$$

for the object to be considered electrically small. Accordingly the frequency specified by

$$|k| \simeq \frac{1}{d} \tag{19}$$

can be considered as an upper frequency for which the model based on an object being electrically small can generally be used for roughly correct results.

Define a relaxation frequency

$$\omega_r \equiv \frac{\sigma}{\varepsilon} \tag{20}$$

For $\omega > \omega_r$ then $\bar{\lambda}$ is the important wave distance; for $\omega < \omega_r$ then δ is the important wave distance. Combining the results for $\bar{\lambda}$ and δ from equations 15 and 16 and comparing these to the object size d we can define a critical radian frequency for considering an object as electrically small as

$$\omega_o \equiv \min\left[\frac{1}{\sqrt{\mu\varepsilon}\,d} , \frac{2}{\mu\sigma d^2}\right] \tag{21}$$

which for the case of $\mu = \mu_o$, $\varepsilon = \varepsilon_o$ reduces to

$$\omega_o = \min\left[\frac{c}{d} , \frac{2}{\mu_o\sigma d^2}\right] \tag{22}$$

where the speed of light is

$$c \equiv \frac{1}{\sqrt{\mu_o\varepsilon_o}} \tag{23}$$

For a given value of d as σ is increased ω_o is given by the first expression based on $\bar{\lambda} = d$ until σ is large enough that the second expression based on $\delta = d$ makes ω_o decrease proportional to

$1/\sigma$. The transition from $\bar{\lambda}$ dominated to δ dominated occurs when the two expressions are equal and at this transition ω_o is of the order of the relaxation frequency ω_r.

This critical radian frequency ω_o can be simply defined as above for the case of time independent σ, ε, and μ. However in an EMP source region of conducting air σ is a time varying quantity which changes significantly on the same time scale as the source current density and the resulting basic electromagnetic quantities. In order to apply the above criterion for determining an upper frequency ω_o for which an object can be considered electrically small then one can use an appropriate time-averaged conductivity where the time averaging is over a time appropriate to the frequency of interest. Thus corresponding to an ω one might average $\sigma(t)$ over a time of the order of $1/\omega$ around the peak σ. If σ has a large peak for a very short time compared to $1/\omega$ then the slowing of the wave propagation for this very short time does not have an appreciable effect over the time $1/\omega$. Thus define $\bar{\sigma}(\omega)$ as the time average of σ over a time $1/\omega$, say centered around the peak if this time is fairly short. One might start this time averaging period at some "zero" time when the EMP is just starting if $1/\omega$ is large compared to the time to peak. This then gives a rough value $\bar{\sigma}(\omega)$ to use for σ when trying to estimate a skin depth as in equation 16 in trying to establish if the object is electrically small at radian frequency ω. In equation 22 noting that $\bar{\sigma}(\omega_o)$ now appears the solution for a critical radian frequency ω_o is now complicated somewhat but can still be found.

Having estimated ω_o then for any $\omega < \omega_o$ one can consider the object electrically small in analyzing the EMP interaction. There are various ways that a current, voltage, etc. on this object might get "inside" somewhere. The object might be an antenna with a signal cable leading from it. Even if ω_o is below the normal operating frequency of the antenna one can still be quite concerned about what is coming in for some $\omega < \omega_o$ because of various intentional or unintentional characteristics in the transfer function from the antenna to various positions in the system. The antenna response itself at $\omega < \omega_o$ can be also much larger in some cases due to the presence of σ associated with $\vec{J}_e$ in the environment at such radian frequencies. Of course the object of interest might not be a deliberate antenna but could represent some other penetration such as a cable entrance, aperture, etc.

In order to determine for any ω whether the object of interest can be approximately considered as electrically small then one must know sufficient information about the conductivity $\sigma(t)$ in the medium (or media) surrounding the object. Thus we need $\sigma(t)$, or at least its significant features, given as part of the environment specification. This does not answer all conductivity related questions. For example since σ is a function of the electric field then the presence of the object of interest can change σ in its vicinity due to the electric field distortion. Furthermore the presence of various materials as part of the object of interest which can themselves have a time changing conductivity (such as insulators in the presence of the nuclear radiation) additionally complicates the EMP interaction. However, the specification of $\sigma(t)$ can still be used to divide the EMP interaction problem into cases which can use approximations for electrically small objects from those which require more detailed calculations of the EMP interaction for approximate results.

Considering the case of electrically small objects, then the EMP interaction is basically quasi static. Referring back to section II then the four basic types of electromagnetic quantities (current density, magnetic field, voltage density, and electric field) take on special significance in that as incident fields, etc. they are approximately uniform over the object of characteristic linear dimension d. Solving a Laplace type equation (perhaps even including nonlinear σ) in the vicinity of the object one can ask how much current here or how much voltage there. Relating these results for current and voltage back to the basic electromagnetic quantities is just a geometrical relation, a sensitivity expressed in meters (a length) or square meters (an area). Of course, this presumes that one is concerned with current or voltage at some defined pair of terminals. One might treat the field penetration through an aperture somewhat differently, but even in the case of an aperture it is interesting to note that the fields penetrating the aperture are proportional to the surface current density and/or surface charge density for the shorted aperture times a geometrical constant associated with the aperture size and shape.[2] Basically the object samples or collects current and/or voltage from the EMP environment proportional to the appropriate electromagnetic quantity in the environment (as in figure 2) and the appropriate length and/or area which is a geometrical property of the object of interest.

For electrically small objects their most important characteristics as low-frequency field radiators are their electric and magnetic dipole moments.[3] Quadrupole and higher order terms are much less effective as radiators and monopole terms are at most a non time changing total electric charge and so not significant for our present considerations. Using reciprocity

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[2] Clayborne D. Taylor, Interaction Note 74, Electromagnetic Pulse Penetration through Small Apertures, March 1971.

[3] Capt Carl E. Baum, Sensor and Simulation Note 125, Some Characteristics of Electric and Magnetic Dipole Antennas for Radiating Transient Pulses, January 1971.

arguments one can conclude the same general results for receiving antennas at low frequencies, namely that the electric and magnetic dipole terms are dominant. If by chance or by design the object has no electric or magnetic dipole interaction (including the effects of nonlinearities in removing some symmetries) referred to some terminals then higher order terms are needed to describe the interaction but are not considered in this note.

Many previous notes have considered the problem of measuring various of the basic electromagnetic quantities in figure 2: current density, magnetic field, voltage density, and electric field. Again for electrically small sensors these reduce to electric and magnetic dipoles operating in open circuit or short circuit mode to measure these four different kinds of basic electromagnetic quantities.[4] In an EMP source region the nonlinear and time varying conductivity as well as the nuclear radiation and its associated source current density make accurate measurements much more difficult than outside of such source regions as in the case of many EMP simulators. Special care must be taken, particularly in the case of electric dipole sensors, to avoid the source current and nonlinearity problems so as to measure the electric field or total current density.[5,6,7] However, even magnetic dipole sensors have significant design problems for optimum performance in EMP source regions.[8,9]

For our present purposes, however, we are not trying to design sensors for accurately measuring source region EMP fields, we are discussing a first order low frequency EMP interaction

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[4] Capt Carl E. Baum, Sensor and Simulation Note 38, Parameters for Some Electrically-Small Electromagnetic Sensors, March 1967.

[5] Lt Carl E. Baum, Sensor and Simulation Note 15, Radiation and Conductivity Constraints on the Design of a Dipole Electric Field Sensor, February 1965.

[6] Lt Carl E. Baum, Sensor and Simulation Note 26, The Influence of Finite Soil and Water Conductivity on Close-in Surface Electric Field Measurements, September 1966.

[7] Capt Carl E. Baum, Sensor and Simulation Note 33, Two Types of Vertical Current Density Sensors, February 1967.

[8] Lt Carl E. Baum, Sensor and Simulation Note 29, The Influence of Radiation and Conductivity on $\dot{B}$ Loop Design, October 1966.

[9] Capt Carl E. Baum, Sensor and Simulation Note 30, The Single-Gap Cylindrical Loop in Non-Conducting and Conducting Media, January 1967.

model for the source region (and outside it as well). Nevertheless the sensor design question is related to the interaction question for electrically small objects because both are basically electric and magnetic dipole questions. Charge deposition can give an electric monopole term for an object but this is not the same as the charge difference (and associated current and volts) at an electrical terminal pair which divides the object. Thus while we do not expect precisely calculable parameters, especially for electric dipole quantities which are significantly affected by the nonlinearities in EMP source regions, still the basic physical processes are the same so that some of the sensor design considerations can be applied to the source region interaction question.

Referring back to figure 2 consider the total current density $\vec{J}_t$. One might have some electric dipole antenna operating in short circuit mode; the short circuit current is related to $\vec{J}_t$ by an equivalent area $\vec{A}_{eq}$ as[4]

$$I_{sc} = -\vec{J}_t \cdot \vec{A}_{eq} \tag{24}$$

This neglects some of the complexities of the interaction of the source current density with the object itself since high energy electrons are both emitted from and collected by the antenna, generally in different quantities. Thus we define a special area $\vec{A}_c$ which may not be the same as $\vec{A}_{eq}$ (in either magnitude or direction) as a sensitivity to the compton current so that we can write

$$I_{sc} = -\vec{J}_e \cdot \vec{A}_{eq} - \vec{J}_c \cdot \vec{A}_c \tag{25}$$

as a more general form for electric dipole interaction in an EMP source region. Note that $\vec{A}_c$ can be dependent on both the spectrum and directional characteristics of the incident photons and high energy electrons. As a first order estimate of $\vec{A}_c$ (or simply $-\vec{J}_c \cdot \vec{A}_c$) one might estimate photon attenuations through various parts of the object and associate a $\vec{J}_c$ in and outside the object with the local photon intensity and direction to calculate total current into and out of various conductors, etc.

Such a short circuit current for an electric dipole can be readily applied to many practical geometries such as a conducting post sticking up out of the ground, the total current crossing the perimeter of an access hatch into a missile site, the total current along a missile in flight, etc. (all at sufficiently low frequencies of course). As one can see this current density response is characteristic of the total current flowing across a defined boundary between two blobs of metal which are shorted together at this boundary. As such this type of response can be quite important. It is not an electric field response but a current density response which involves not only the displacement current density but the conduction current density and the compton current density as well. To estimate the response of this type of antenna in an EMP source region only using the electric field without the conductivity, for example, is meaningless and can be off by several orders of magnitude because the farther into the source region one goes the more the displacement current density is dominated by the conduction current density. If one measures the response of such an object in short circuit conditions in an EMP simulator which only has free space conditions (no air conductivity, compton current density, etc.) the electric field cannot be used to directly scale the current to the particular source region environment electric field. Rather, the displacement current density (plus conduction, if present) in the simulator can be used to scale the short circuit current to the environment $\vec{J}_e$, comprising both conduction and displacement current density; the response to the source current density must still be estimated and added into the result.

In open circuit conditions an electric dipole object has an open circuit voltage in response to the electric field related through an equivalent height $\vec{h}_{eq}$ as

$$V_{oc} = -\vec{E} \cdot \vec{h}_{eq} \tag{26}$$

One can think of this roughly as the potential developed between two separate conductors in the EMP environment. The presence of the source current density can alter the result of equation 26 because the net current transferred between the two conductors associated with the photons and high energy electrons flows through the antenna impedance Z_e to give a corrected open circuit voltage

$$V_{oc} = -\vec{E} \cdot \vec{h}_{eq} - Z_e \vec{J}_c \cdot \vec{A}_c \tag{27}$$

Since the conductivity can be changing with time the use of Z_e as in equation 26 is only approximate, but it can be replaced by appropriate time domain operators.

If the electric dipole object in the source region is simply two highly conducting objects immersed in a uniform medium with no additional insulators of any significance then neglecting nonlinearities the admittance of the object is

$$Y_e = \frac{1}{Z_e} = G_e + sC_e \tag{28}$$

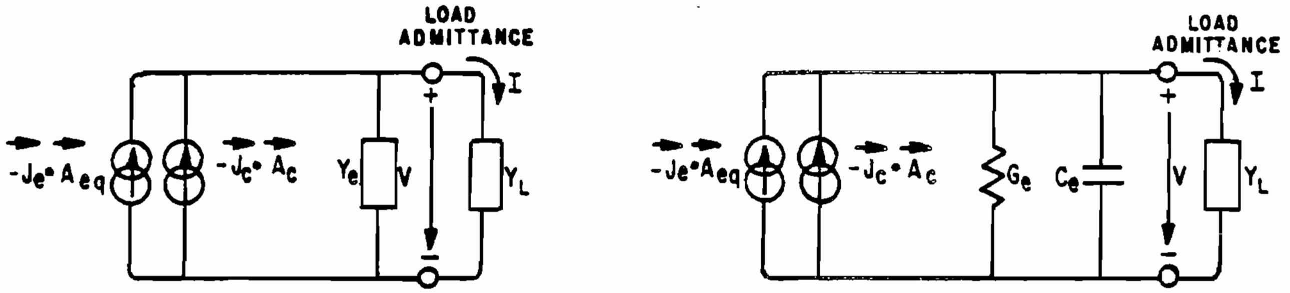
where the conductance and capacitance are related through the medium parameters as

$$\frac{G_e}{\sigma} = \frac{C_e}{\varepsilon} \tag{29}$$

Remember that this description strictly holds only if the antenna is electrically small. Note that the conductance G_e is just some geometric constant of the antenna times σ, the medium conductivity, and is thereby a function of time.

If additional media with different conductivity and/or permittivity are present in the vicinity of the electric dipole object conductors, then the response is complicated somewhat. The admittance as in equation 28 might be more complex with appropriate series and/or parallel combinations of conductances and capacitances corresponding to the geometric arrangement of the various additional media with respect to the conductors. To some extent the complexities of the air, ground, etc. under radiation in an EMP source region can also give these kinds of effects such as by boundary layers next to the conductors.[5] Often in EMP source regions σ is large enough so that G_e is the dominant admittance term and the equivalent area $\vec{A}_{eq}$ and equivalent height $\vec{h}_{eq}$ can be calculated as boundary value problems involving perhaps an inhomogeneous conducting medium depending on the various materials subject to radiation in the vicinity of object conductors. This admittance, equivalent area, and equivalent height could be somewhat different from those applying outside an EMP source region, such as in non conducting air where with insulators present the capacitive admittance dominates and the permittivity distribution is involved in calculating $\vec{A}_{eq}$ and $\vec{h}_{eq}$. In the absence of significant additional media, however, the equivalent height and equivalent area are approximately independent of frequency and the conductivity (except for nonlinearities) and the simple relation between the conductance and capacitance as in equation 29 is roughly correct.

As a first order equivalent circuit for an electrically small electric dipole object in an EMP source region we have the Norton and Thevenin forms shown in figure 5. The Norton form as in figure 5A is the form appropriate for the short circuit current as in equation 25. The Thevenin form in figure 5B is the form appropriate for the open circuit voltage as in equation 27. When considering the source current density interaction with an electric dipole type of object the Norton form is more convenient because of its direct use of current density for the source in the equivalent circuit; the Thevenin equivalent circuit has the source current density $\vec{J}_c$ converted to an equivalent electric field. The equivalent area and equivalent height are related as



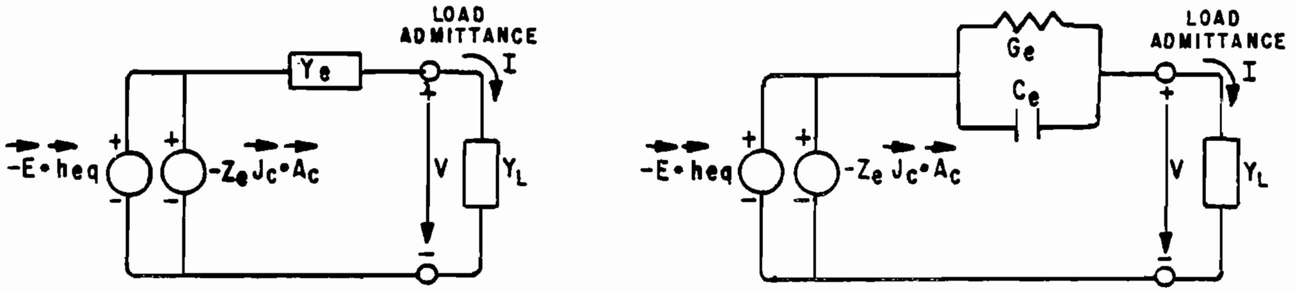
Y_e REPRESENTS A MANY ELEMENT RC CIRCUIT WITH TIME DEPENDENT ELEMENTS.
$\vec{A}_{eq}$ IS TIME DEPENDENT.

GENERAL CASE

G_e IS PROPORTIONAL TO $\sigma(t)$.
$\vec{A}_{eq}$ IS TIME INDEPENDENT.

SIMPLE CASE

A. NORTON FORM (LINEAR)



$Y_e (= Z_e^{-1})$ REPRESENTS A MANY ELEMENT RC CIRCUIT WITH TIME DEPENDENT ELEMENTS.
$\vec{h}_{eq}$ IS TIME DEPENDENT.

GENERAL CASE

G_e IS PROPORTIONAL TO $\sigma(t)$.
$\vec{h}_{eq}$ IS TIME DEPENDENT.

SIMPLE CASE

B. THEVENIN FORM (LINEAR)

FIGURE 5. APPROXIMATE EQUIVALENT CIRCUIT FOR AN ELECTRICALLY SMALL ELECTRIC DIPOLE OBJECT IN AN EMP SOURCE REGION

$$\vec{J}_e \cdot \vec{A}_{eq} = Y_e \vec{E} \cdot \vec{h}_{eq} \tag{30}$$

For the simple-medium case where Y_e is the parallel combination of conductance and capacitance related to the medium parameters as in equation 29 this reduces to

$$\begin{aligned} \sigma \vec{A}_{eq} &= G_e \vec{h}_{eq} \\ \epsilon \vec{A}_{eq} &= C_e \vec{h}_{eq} \end{aligned} \tag{31}$$

Even if Y_e is more complex the fact that $\vec{J}_e$ is parallel to $\vec{E}$ for many cases of interest allows one to conclude that for such cases $\vec{A}_{eq}$ and $\vec{h}_{eq}$ are also parallel.

Strictly speaking the electric dipole admittance Y_e (just as its inverse, the impedance Z_e) is not an admittance in the sense of a complex number (units mhos) which one multiplies a frequency domain voltage to obtain a frequency domain current. Neglecting nonlinearities (which can be significant) Y_e can better be considered as an operator relating time domain voltage and current where some of the coefficients in the operator are themselves functions of time. Y_e can then be considered as a representation of an electrical RC network (corresponding to conductivities and permittivities of the local media) with element values changing as a function of time. For many cases of interest the electric dipole is simple enough to approximate as the simple case as shown in figure 5 with time independent $\vec{A}_{eq}$ and $\vec{h}_{eq}$, time dependent conductance $G_e(t)$, and approximately time independent capacitance C_e. The electric dipole is driving some kind of load admittance Y_L which might come from a cable, some network, etc. The relative size of Y_L compared to Y_e is quite important because it determines which of the two basic responses, to current density or to electric field, characterizes the performance of the electric dipole and thereby the interaction of the object of interest in the EMP source region. Generally speaking the conductivity dominates the permittivity in the source region. Thus $G_e(t)$ in comparison to the typical value of Y_L (which might be a simple conductance) is important. Making this comparison one can characterize the electric dipole performance as short circuit, open circuit, or perhaps short circuit for part of the time domain and open circuit for the remainder. To know $G_e(t)$ one must know $\sigma(t)$. Thus for the basic performance of an electric dipole antenna in an EMP source region one should have specified as part of the environment the conductivity time history (or histories for more than one medium) so as to characterize the electric dipole as sensitive to the current density or the electric field, two fundamental features of the environment which should also be specified. For an electric dipole object the conductivity is not just important for deciding a critical radian frequency ω_o below which the antenna is electrically small; the conductivity is fundamentally important to its performance, even though it is electrically small. Not only are the air and ground conductivity important; the conductivities of any additional media of significance placed locally around the electric dipole object are important and these may change under the influence of the nuclear radiation, thereby requiring knowledge of the nuclear radiation such as involved in an ionization rate such as S_e.

It would be difficult to overemphasize the fundamental importance of the current density and conductivity in addition to the electric field in EMP source region interaction. One can envision various different examples of practical objects which in the electrically small case are electric dipoles, many typically operating in short circuit mode. Figure 6 shows several typical examples. A previous interaction note considers a particular example of electric dipole antenna--a deliberate one--and some of the numbers associated with its EMP source region interaction.[10]

Now consider the magnetic dipole case. The short circuit current is related to $\vec{H}$ by an equivalent length $\vec{\ell}_{eq}$ as[4]

$$I_{sc} = \vec{H} \cdot \vec{\ell}_{eq} \tag{32}$$

This has not included the direct interaction of the source current density with the magnetic dipole object. With the electrical terminals shorted and considering the current flowing in a distributed manner over the entire object which we take as highly conducting and as basically a loop then in the static limit the source current density generates currents in the conductors proportional to $\vec{J}_c$ due to high energy electrons being captured by the object and being knocked off the object by the high energy photons. The constant of proportionality is an area $\vec{A}_c$ which relates $\vec{J}_c$ to the short circuit current at the defined electrical terminals. Thus we correct equation 32 to give the total short circuit current as[8]

$$I_{sc} = \vec{H} \cdot \vec{\ell}_{eq} - \vec{J}_c \cdot \vec{A}_c \tag{33}$$

The minus sign on the second term is chosen to make this term the same as for the electric dipole short circuit current as in equation 25 since the interaction of $\vec{J}_c$ with the object to give

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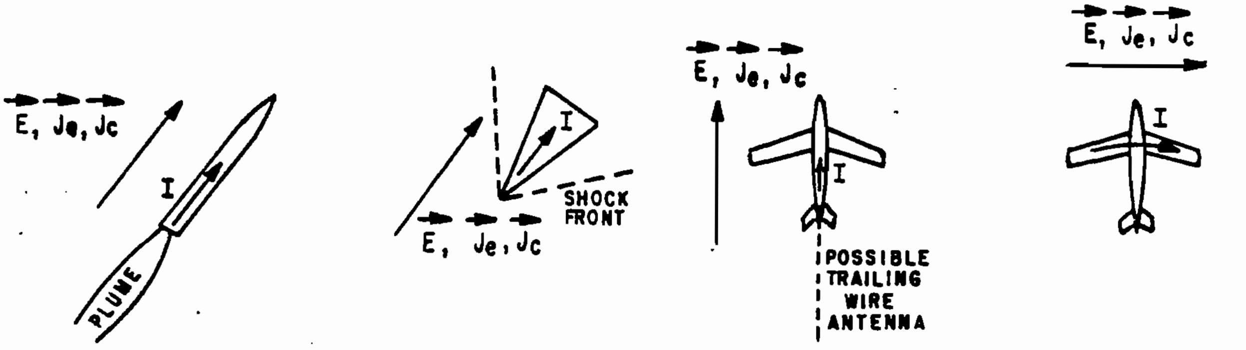
[10] Conrad L. Longmire, Interaction Note 69, Direct Interaction Effects in EMP, January 1971.



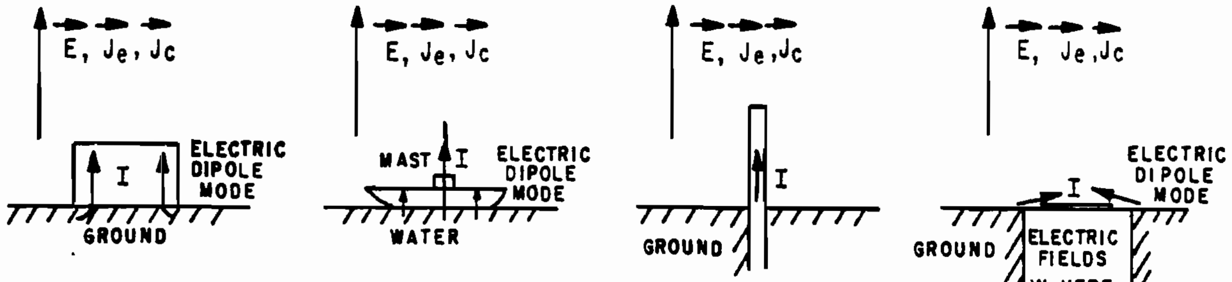
MISSILE

REENTRY VEHICLE

AIRCRAFT: SYMMETRIC MODE

AIRCRAFT: ANTISYMMETRIC MODE

A. IN-FLIGHT SYSTEMS



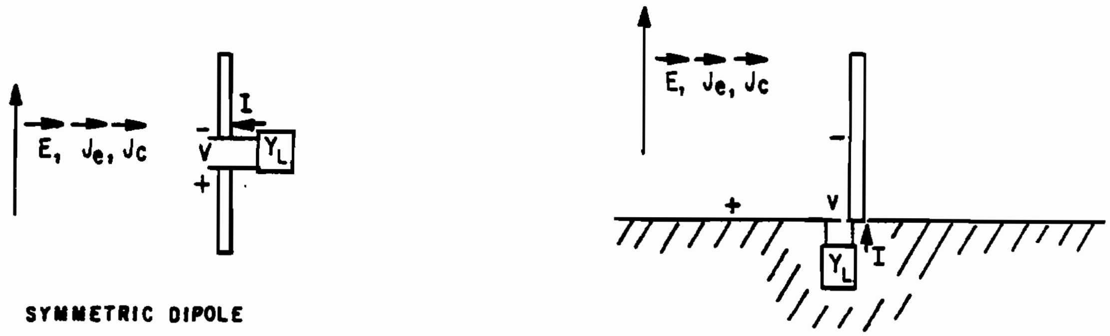
BUILDING WITH CONDUCTING FRAME OR WALLS

SHIP

CONDUCTING POST

CLOSURE AT GROUND SURFACE

B. OBJECTS NEAR THE GROUND OR WATER SURFACE



SYMMETRIC DIPOLE

DIPOLE ON GROUND PLANE

C. ELECTRIC DIPOLE ANTENNAS

FIGURE 6. SOME EXAMPLES OF OBJECTS WHICH BEHAVE AS ELECTRIC DIPOLES IN THE LIMIT OF BEING ELECTRICALLY SMALL

the short circuit current is basically the same for both electric and magnetic dipole type objects. While $\vec{A}_c$ will generally be proportional to the geometric cross section area of the object, other problems involving detailed photon and electron transport are involved and complicate the calculation of $\vec{A}_c$ somewhat.

The open circuit voltage of a magnetic dipole responds to the voltage density as

$$V_{oc} = \frac{\partial \vec{B}}{\partial t} \cdot \vec{A}_{eq} = \vec{W} \cdot \vec{A}_{eq} \tag{34}$$

If the impedance of the object at its terminals is Z_m then the effect of the source current density can be included in the open circuit voltage as

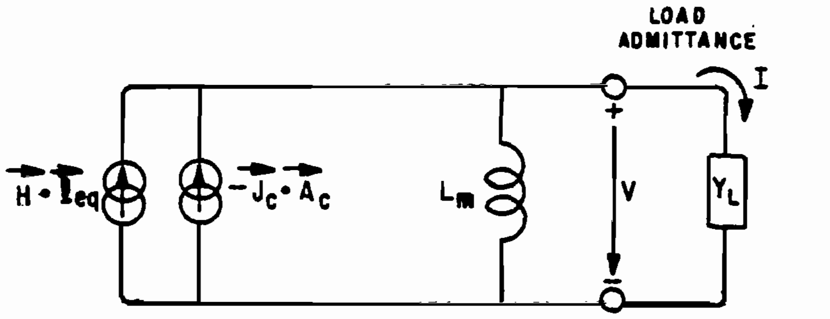
$$V_{oc} = \frac{\partial \vec{B}}{\partial t} \cdot \vec{A}_{eq} - Z_m \vec{J}_c \cdot \vec{A}_c = \vec{W} \cdot \vec{A}_{eq} - Z_m \vec{J}_c \cdot \vec{A}_c \tag{35}$$

The impedance of a magnetic dipole object for the case that it is electrically small is basically

$$Z_m = \frac{1}{Y_m} = sL_m \tag{36}$$

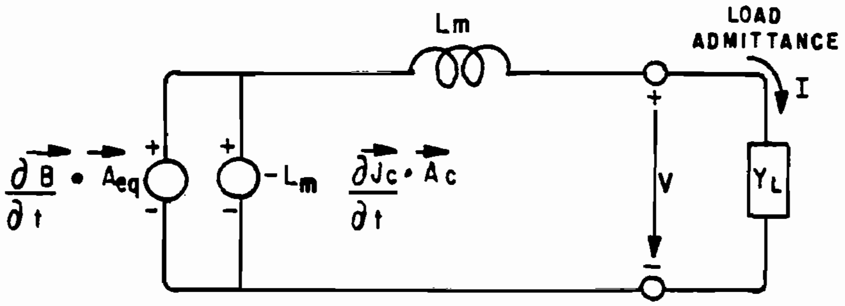
Note that the conductivity does not even enter this result, thereby making a magnetic dipole a much simpler object to consider in an EMP source region than an electric dipole object. There may be various conducting dielectric layers around the object but these have no effect on $\vec{A}_{eq}$ or Z_m. On the other hand if the permeability μ is a function of position around the object then the equivalent area and impedance can be altered. However, since μ is not changed like σ (and perhaps ε) by the nuclear radiation then $\vec{A}_{eq}$ and L_m are independent of time as long as the object is electrically small. Often μ is just the permeability of free space μ_o, making the problem even simpler.

As a first order equivalent circuit for an electrically small magnetic dipole object in an EMP source region we then have the Norton and Thevenin forms shown in figure 7. The Norton form as in figure 7A corresponds to the short circuit current viewpoint in equation 33. The Thevenin form as in figure 7B corresponds to the open circuit voltage viewpoint in equation 35. Using the form of Z_m in equation 36 the open circuit voltage in equation 35 can be written as



SENSITIVITY TO $\vec{J}_e$ IS NEGLECTED IN THIS CIRCUIT.
SENSITIVITY TO $\vec{J}_c$ CAN OFTEN ALSO BE NEGLECTED.

A. NORTON FORM



SENSITIVITY TO $\vec{J}_e$ IS NEGLECTED IN THIS CIRCUIT.
SENSITIVITY TO $\vec{J}_c$ CAN OFTEN ALSO BE NEGLECTED.

B. THEVENIN FORM

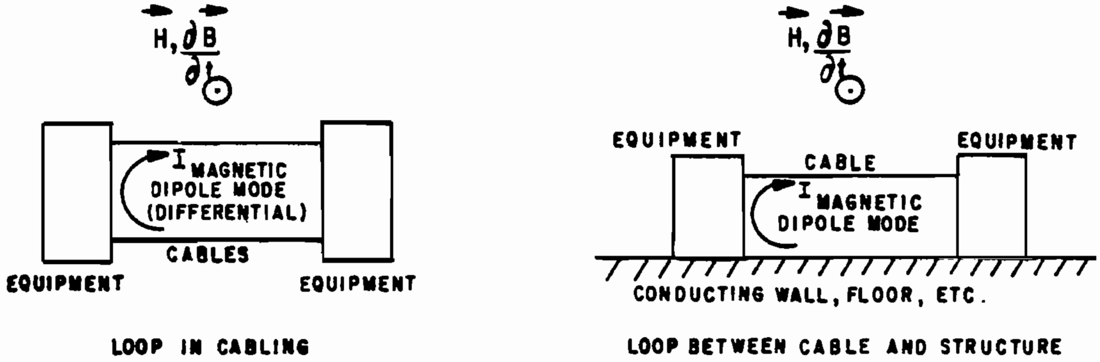
FIGURE 7. APPROXIMATE EQUIVALENT CIRCUIT FOR AN ELECTRICALLY SMALL MAGNETIC DIPOLE OBJECT IN AN EMP SOURCE REGION

$$V_{oc} = \frac{\partial \vec{B}}{\partial t} \cdot \vec{A}_{eq} - L_m \frac{\partial \vec{J}_c}{\partial t} \cdot \vec{A}_c \tag{37}$$

which is a completely time domain form. Due to the complexity of Z_e for a general electric dipole object in inhomogeneous conducting dielectric media this simple result for the open circuit voltage applying to magnetic dipole objects does not always have a comparable simple result for electric dipole objects. Note that associated with the complexities of the photon and electron transport the collection area $\vec{A}_c$ for the source current density interaction with electric and magnetic dipoles can be a function of $\vec{J}_c$, even changing direction (which can also be considered as a matrix type of property). In such more general form the open circuit voltages and short circuit currents for both electric and magnetic dipole interaction with the nuclear radiation takes on greater complexity but is still an additive term in the above equations.

One feature of the magnetic dipole case is the simple quantitative relation between its short circuit response to $\vec{H}$ and its open circuit response to $\partial\vec{B}/\partial t$; the two responses are related by an inductance L_m and a time derivative or integral (from s in sL_m). The inductance L_m is a geometric constant of the object which is not typically affected by the nuclear radiation. Furthermore $\vec{B}$ and $\vec{H}$ are related by the permeability μ which is typically μ_o. Thus if one specifies either $\partial\vec{B}/\partial t$ or $\vec{H}$ the other can be directly and simply inferred. One might argue then that one needs only one of these in an environment specification in frequency and time domains. There is, however, a certain logical consistency to specifying both in analogy to the electric dipole case where both $\vec{J}_e$ and $\vec{E}$ are needed. Together with $\vec{J}_c$ then we can have most directly both open circuit voltage and short circuit current for both electric and magnetic dipoles. Figure 8 shows several typical examples of magnetic dipole types of interactions.

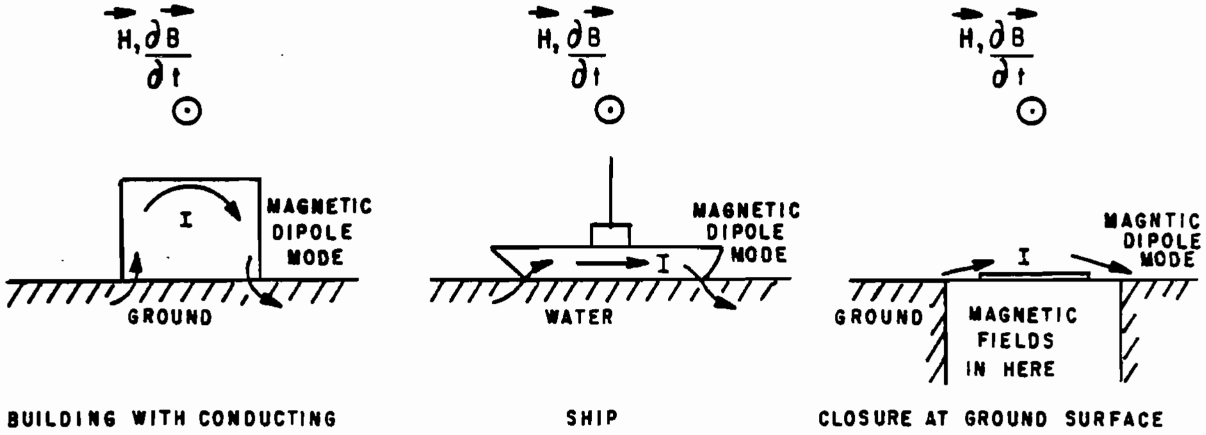
Note that while sources to represent the direct radiation induced signal are included in the equivalent circuits for both electric and magnetic dipoles (figures 5 and 7 respectively) they are not in general of the same relative importance in the two cases. For the electric dipole $\vec{J}_c$ can be compared to $\vec{J}_e$ and the two are of the same order, being equal and opposite in the simple case of curl $\vec{H}$ being zero. Such a case applies, for example, to the spherically symmetric (approximately so) nuclear air burst where the source region does not intersect the ground. If $\vec{A}_{eq}$ and $\vec{A}_c$ are comparable for the electric dipole then for low frequencies that the dipole is electrically small the radiation induced signal is comparable to that associated with $\vec{J}_e$ (or $\vec{E}$). For the magnetic dipole, however, the situation is somewhat different. As discussed in reference 8, as the frequency is lowered the magnetic dipole response to $\vec{H}$ (say in short circuit



LOOP IN CABLING

LOOP BETWEEN CABLE AND STRUCTURE

A. LOOPS IN SYSTEMS

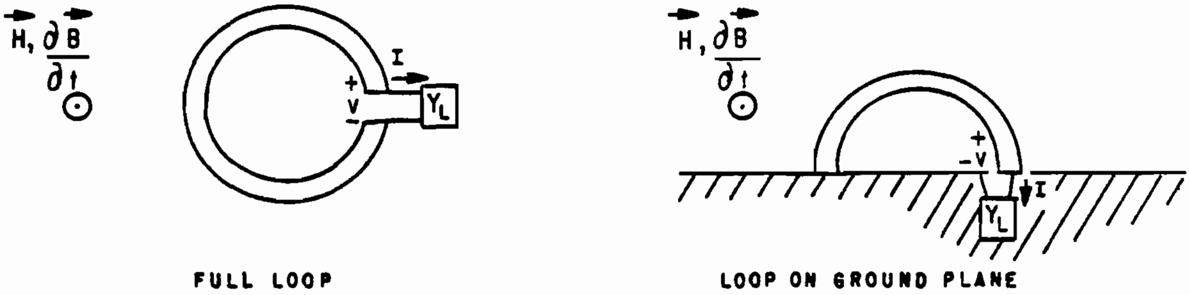


BUILDING WITH CONDUCTING

SHIP

CLOSURE AT GROUND SURFACE

B. OBJECTS NEAR THE GROUND OR WATER SURFACE



FULL LOOP

LOOP ON GROUND PLANE

C. MAGNETIC DIPOLE ANTENNAS

FIGURE 8. SOME EXAMPLES OF OBJECTS WHICH BEHAVE AS MAGNETIC DIPOLES IN THE LIMIT OF BEING ELECTRICALLY SMALL

mode) tends to dominate that from $\vec{J}_c$. For a near surface burst with observer near the surface, as the frequency is lowered the skin depth in the surrounding medium is increased and $\vec{H}$ is proportional in magnitude to $\vec{J}_c$ times the skin depth. Looking at the Norton equivalent circuit in figure 7A both $\vec{H}$ and $\vec{J}_c$ enter the same way. Thus for fixed $\vec{\ell}_{eq}$ and $\vec{A}_c$ if one goes down in frequency the signal from $\vec{H}$ will eventually dominate that from $\vec{J}_c$, considering only the response for $\vec{H}$ with a significant component in the direction of $\vec{\ell}_{eq}$. Thus in a low frequency model one might sometimes neglect the sensitivity of a magnetic dipole to $\vec{J}_c$.

In addition to the magnetic dipole sensitivity to the source current density $\vec{J}_c$ one can also include a generator in the equivalent circuit to represent the sensitivity to $\vec{J}_e$, with the same kind of interaction (an equivalent area) describing the contribution of $\vec{J}_e$ to the short circuit current. However, since $\vec{J}_e$ tends to be of the same order as $\vec{J}_c$ in an EMP source region then the sensitivity to $\vec{J}_e$ is negligible at sufficiently low frequencies just as in the case of $\vec{J}_c$. By using insulators around magnetic dipole sensors the sensitivity to $\vec{J}_e$ can be made much smaller in an EMP source region. In the case of free space media this sensitivity to $\vec{J}_e$ is often termed the "electric field sensitivity" of a loop. As frequency is decreased this sensitivity becomes negligible for the ratio of $|\vec{E}|$ to $|\vec{H}|$ of the order of the wave impedance of the medium.

In applying this first order dipole interaction model to electrically small objects one should try to separate the basic interaction of the object with the EMP to produce current and volts from what gets to some circuit, etc. inside the system. The various networks (cabling etc.) can superimpose a complex transfer function on the basic dipole response. Such a transfer function can also include various elements that are physically part of what one considers as the basic dipole structure, such as inductive shorts or other more complex elements loading what one defines as the electrical terminal pair in treating the object as a dipole antenna. Even some kinds of internal field coupling such as from apertures to cabling etc. can be approximately described by transfer functions which take as an input a signal from an equivalent dipole model of the aperture.

In characterizing electrically small objects as electric or magnetic dipoles note that it is quite possible for both dipole moments to be important. One can use both dipole moments to make efficient low frequency radiating antenna systems;[3] one can design electromagnetic sensors utilizing both dipole moments.[11]

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[11] R. E. Partridge, Sensor and Simulation Note 3, Combined E and $\dot{B}$ Sensor, February 1964.

The low-frequency interaction problem can have the same feature. As an example a typical shielded loop with differential output onto a twinax cable is a magnetic dipole type of object for the differential mode. If the conducting loop connected to the differential output is not shorted to the shield as well, then a large common mode signal can be developed. Even if the loop is shielded the nuclear radiation driven current density $\vec{J}_c$ can penetrate the shield and a net current source can drive the common mode with a capacitance and perhaps also a parallel conductance for the common mode source admittance; the common mode is then driven in this case by an electric dipole type of object. The same object can then behave as different types of dipoles with respect to different independent output signals at the various output terminals of interest.

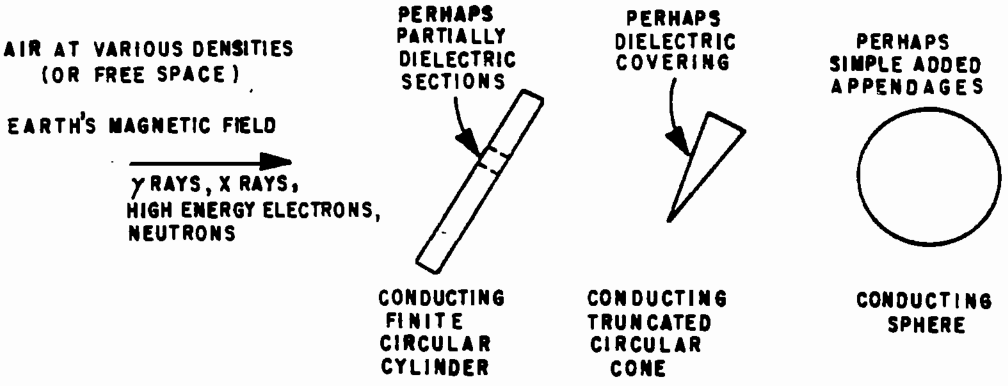
IV. Some Idealized Geometries Appropriate to EMP Interaction in a Nuclear Source Region

While the dipole model is a useful first order model for EMP interaction, including the cases of both inside and outside of nuclear source regions, it still has limitations. In non conducting media if the wavelength is of the order of the size of the object of interest then resonances can occur on the object and these are not included in a simple dipole model as discussed in section III. For yet higher frequencies in non conducting media higher order resonances can occur until at sufficiently high frequencies geometrical optics and diffraction theory provide a better way to look at the interaction problem. In conducting media as the skin depth becomes of the order of or less than the size of the object the simple dipole model breaks down. The skin depth phenomenon has attenuation associated with it and this can reduce the fields etc. reaching an object by propagating through the conducting medium. However, in a nuclear source region the fields etc. are locally generated, i.e. right within a skin depth of the object, so such propagation attenuation does not apply to interaction in EMP source regions. Also in EMP source regions there are nonlinearities which restrict the accuracy of the dipole model, at least for the electric dipole, because of the use of linear equivalent circuits.

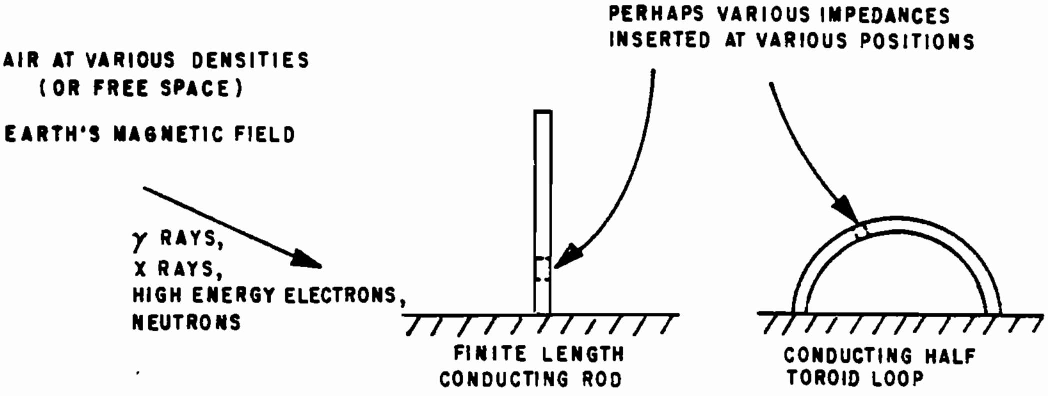
Particularly, then, for electric dipole type objects it would be desireable to make detailed calculations of their responses in EMP source regions even for frequencies such that they are electrically small because of the nonlinearities involved in the conductivity (particularly air conductivity). In addition the presence of other dielectric material (possibly conducting as well) in the immediate vicinity of the object (perhaps enclosing it) can complicate the problem significantly for an electric dipole because of nonlinear effects in these media even though the object be electrically small. As the frequency is increased both electric and magnetic dipole type objects are not electrically small; more detailed calculations are needed for both types for high frequencies (actually fast times in the time domain) including both the time varying and nonlinear properties of the various media.

For objects that are electrically small in EMP source regions for some frequencies of interest one may profitably study their performance with detailed calculations and experiments using the correct nuclear radiation and surrounding media. The purpose of such calculations would be to quantify nonlinear and high frequency effects and determine for what low frequencies the simple dipole model applies and to what extent nonlinearities alter the results (especially for electric dipoles) at low frequencies. However actual objects of interest can be rather complex making analytical and/or numerical calculations quite difficult. In order to quantify some of the effects for high frequencies (fast times) and nonlinearities one might then choose simplified geometries and materials for idealized objects which have responses in EMP environments which include the various physical processes which affect the response of real objects of interest (including metal conductors, dielectrics, etc.). One might consider the solution of such interaction cases, theoretically and/or experimentally, as canonical problems for the general source region interaction question.

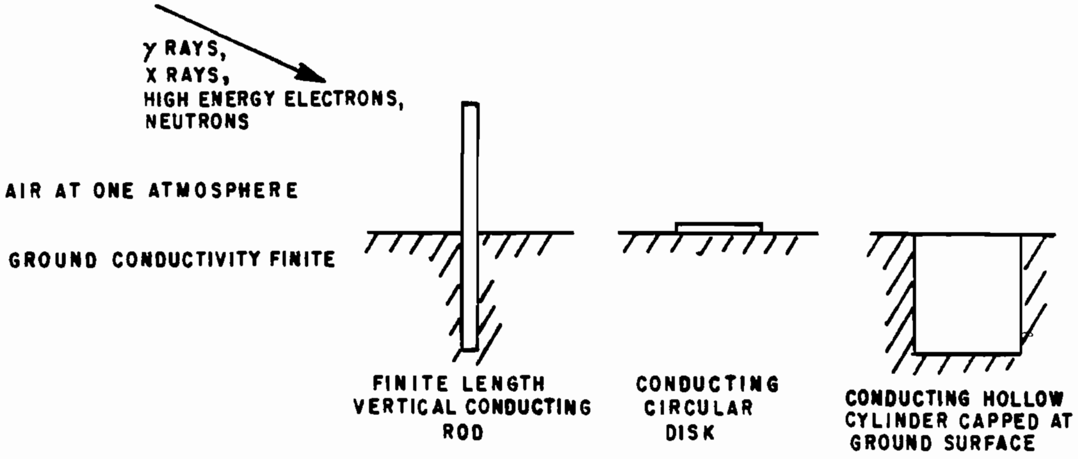
Considering various types of structures such as those in figures 6 and 8 one can envision simplified structures which represent the essential features of the geometry and materials of the real objects. Some of the simplest cases of canonical problems for objects which are electrically small in EMP source regions at some frequencies of interest are shown in figure 9. Consider geometries characteristic of say missile and space systems. One might treat some of these through idealized geometries as in figure 9A. Finite conducting cylinders with various partial dielectric sections represent missiles; truncated cones represent missiles and reentry vehicles. One might use any of these objects or say a sphere with perhaps various simple appendages or apertures for detailed source region calculations. Note for the exoatmospheric case for such calculations that the system is the source region. Then these kinds of detailed calculations can cover a rather broad range of source region interaction phenomena by varying such things as atmospheric density and object geometry. As shown in figure 9B one can consider various types of appendages such as deliberate antennas on conducting objects where the rest of the object determines the "incident" fields, current density, etc. at these appendages which can in turn be considered as electric and magnetic dipoles; for an exoatmospheric system the bulk of the system would determine the major features of the EMP source region in which these smaller electric and magnetic dipoles are placed. Another class of problems as shown in figure 9C would involve simple geometries of conductors in the vicinity of a ground-air interface where



A. OBJECTS IN AIR OR FREE SPACE



B. OBJECTS ON PERFECTLY CONDUCTING SURFACES



C. OBJECTS NEAR A GROUND SURFACE

FIGURE 9. SOME CANONICAL PROBLEMS FOR EMP SOURCE REGION INTERACTION WITH OBJECTS THAT ARE ELECTRICALLY SMALL AT SOME FREQUENCIES OF INTEREST

the finite ground conductivity is significant. Figure 9C shows a conducting post protruding from the ground, a conducting ground plane, and a capped conducting cylinder which could represent a missile silo. Clearly various other simplified geometries representing buildings, ships on the ocean, etc. can also be considered in detail. These can then be modified to include protrusions for antennas, structural members, cables, etc. and apertures for antennas, hatch closures, etc. Thus there are numerous idealized geometries that can represent objects that are electrically small for some frequencies of interest in EMP source regions and can introduce significant simplifications in calculations of source region interaction phenomena.

There are some kinds of objects which one might not consider electrically small in EMP source regions at any frequencies of interest because of their extremely large size. The simple dipole model discussed in section III does not directly apply in such cases. However, one can use some of the simple physical processes discussed in arriving at that model to very roughly estimate some of the interaction results. Suppose that one is interested in the current, voltage, and/or source impedance at some terminal pair. Then for some frequency or time regime of interest one can estimate based on skin depths in the air, ground, or other media around or part of the object what portions of these media can influence the results at the terminal pair of interest. Then considering only these portions of the media with their boundaries as the object of interest one can consider this modified object for its electric and/or magnetic dipole characteristics. It can integrate current density and voltage density over a skin depth dominated area, and electric field and magnetic field over a skin depth dominated length. Since the skin depth of interest in the source region is smaller than the object size by hypothesis, then the collection areas and lengths are generally smaller than those associated with the complete object. However, there can be exceptions to this general result, particularly if the object geometry has the portion more than a skin depth away from the "terminals" in a configuration to partially cancel the signal integrated from the first skin depth, the cancellation (or signal reduction) only occurring when the farther portion of the object comes within a skin depth (or diffusion depth) of the "terminals."

Just as with the case of objects which are electrically small in EMP source regions one can perform detailed source region calculations for electrically large objects for which the effects of the finite object size are not significantly observed at the "terminals" in times of interest. In this case one can neglect the far end or ends of the object and the geometry can sometimes be made simpler by purposely extending these ends to infinity for the purpose of detailed calculations. Note that this extension to infinity is for the electromagnetic calculations and may not be legitimate in some cases for the nuclear radiation transport and high energy electron transport which can have influence over distances greater than some skin depths. Note that even those objects which are electrically small in EMP source regions for some frequencies of interest can easily be electrically large for other higher frequencies of interest. Thus detailed calculations in EMP source regions for infinite and semi infinite idealized geometries can be applied to many objects of practical interest, at least for sufficiently fast times or high frequencies.

Figure 10 shows what might be thought of as some canonical problems involving infinite and semi infinite geometries. Figure 10A shows some examples in an air or free space medium such as cylinders, cones, and planes which can be considered in infinite and semi infinite versions. Various types of dielectric coatings or sections can be included and various simple protrusions added. Referring back to figure 9A the infinite and semi infinite geometries can be used for calculating portions of the more general problems involving the finite geometries. In figure 10B we have shown some infinite and semi infinite geometries in the vicinity of a ground-air interface. The infinite and semi infinite vertical conducting rod geometries can be used to obtain information applicable to a large number of practical objects of interest, at least for early times and high frequencies. The infinite vertical conducting rod represents a very convenient geometry with boundaries that neatly fit a cylindrical coordinate system; such a geometry is then comparatively well suited to detailed numerical solution involving finite differencing of space and time. Another geometry near the ground surface might involve a semi infinite hollow cylinder in the ground with a cap at the ground surface; this could apply to the missile silo interaction problem. One can also consider a semi infinite vertical post attached (perhaps through impedances) to semi infinite or infinite wires which are parallel to the ground surface. Such a geometry would apply to EMP source region interaction with power and communication lines connecting into various kinds of systems.

Thus while for many frequencies of interest various objects of interest in EMP source regions cannot be considered as electrically small, still all is not lost. One can still make estimates of the interaction using rough physical approximations based on dipole models of relevant portions of the object. Furthermore one can perform more detailed calculations of the interaction including the time varying nonlinear media, but using idealizations of the total object geometry or only the most important parts of the geometry. Such detailed calculations can be both analytical and numerical in nature. In addition experiments using these idealized geometries in nuclear weapon environments and/or in simulated nuclear radiation environments can be performed to compare the results and thereby test the adequacy of the various physical processes included in the

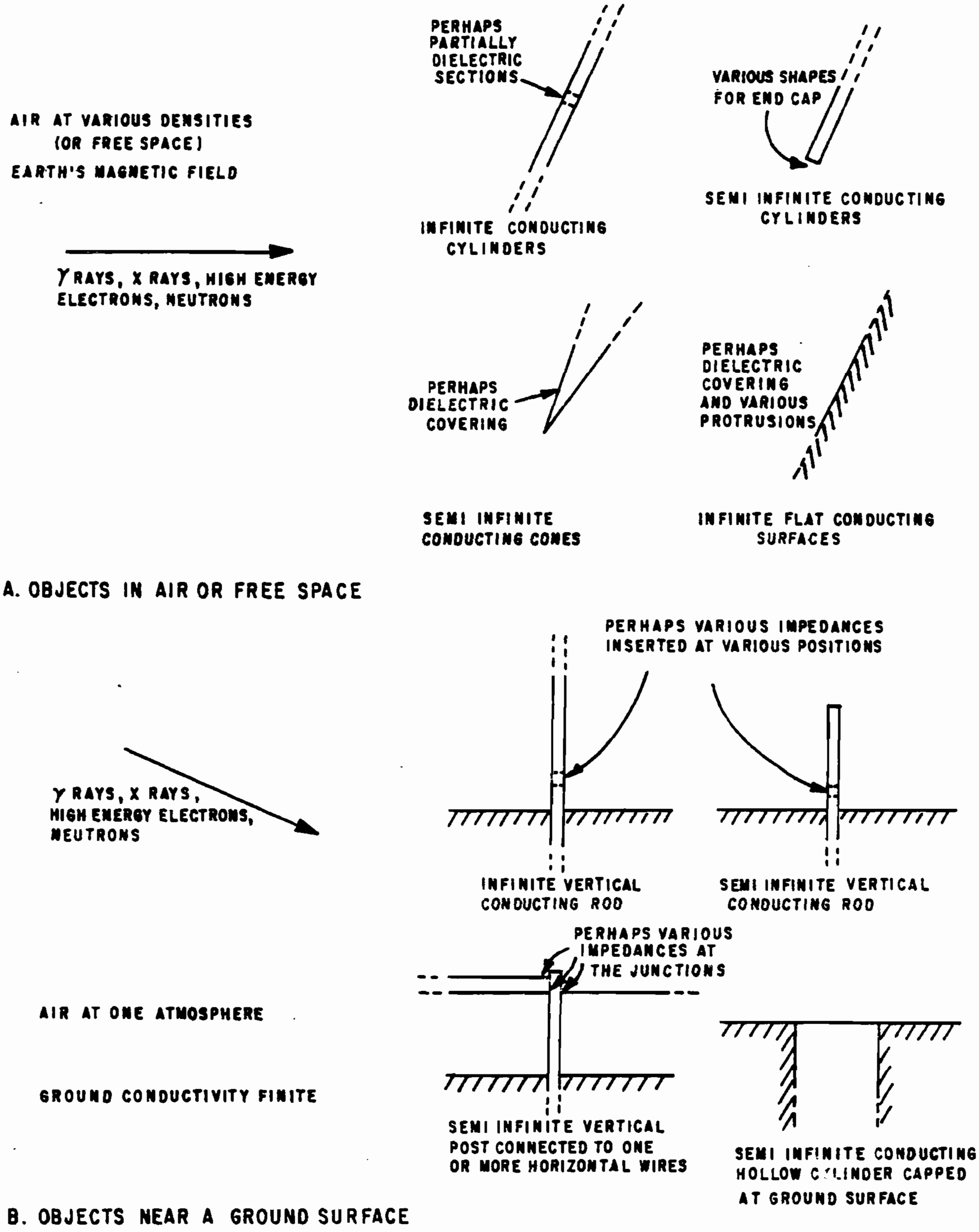


FIGURE 10. SOME CANONICAL PROBLEMS FOR EMP SOURCE REGION INTERACTION WITH OBJECTS THAT ARE ELECTRICALLY LARGE AT SOME FREQUENCIES OF INTEREST

calculations. Different idealized geometries can then be used to emphasize various physical processes and thereby allow more critical tests of the adequacy of the physical parameters incorporated in the calculations, both as to numerical values of the parameters and the presence (or absence) of other important physical processes.

V. Summary

The interaction of the nuclear electromagnetic pulse with objects of interest can be fairly complex, particularly if the object is located in an EMP source region involving source currents and nonlinear time-changing media. However, a simple first order model based on electric and magnetic dipoles can be used to calculate the interaction for frequencies (or times) such that the object can be considered electrically small. An electrically small object (at some particular frequency) is one with maximum linear dimension smaller than the magnitude of the complex radian wavelength in the surrounding medium. The complex radian wavelength is basically the radian wavelength for $\omega > \sigma/\varepsilon$ and the skin depth for $\omega < \sigma/\varepsilon$ where σ and ε are chosen as appropriate average values over times of interest if they happen to be functions of time.

The basic electromagnetic quantities for characterizing an EMP environment are four kinds of vector quantities: the magnetic field $\vec{H}$, the voltage density $\partial\vec{B}/\partial t$, the electric field $\vec{E}$, and the total current density which can be split into two somewhat distinct parts as an electric-field-associated current density $\vec{J}_e$ and a source current density $\vec{J}_c$. Collectively these are the lowest order electromagnetic quantities and are directly related to the open circuit and short circuit characteristics of electric and magnetic dipoles. These relations are basically ones of surface and line integrals over areas and lengths appropriate to the object of interest and its immediate surroundings. However, if various different conducting dielectric media surround electric dipoles their interaction can be altered. There are some secondary parameters which should be included with specifications of EMP source region environments such as conductivity and ionization rates (or even more detailed aspects of the nuclear radiation) because of their influence on the EMP interaction with objects.

For most cases of interest the permeabilities of importance for the surrounding media are just μ_o so that the magnetic field and voltage density are quite simply related and one would not need to specify both, except for consistency with the electric field and current density which are required for the electric dipole interaction. For the basic vector quantities various information, not just the peak, is needed to characterize them. They need characterization for polarization, rise time, pulse widths, and any other peculiar time domain features, and they need similar characterization in the frequency domain for their general characteristics over large frequency bands.

The general considerations in this note apply not only to EMP source regions but outside the source regions as well where the interaction processes are somewhat less complex. A special case, however, is the exoatmospheric system which is illuminated by the nuclear radiation from a weapon. Then one can only specify this nuclear radiation. The object interaction with the nuclear radiation makes an EMP source region in the vicinity of the system. The simple dipole model can then be applied to various parts of the system viewed as electric and magnetic dipoles in the presence of an environment associated with the total system structure.

For electrically large objects in EMP source regions the simple dipole model does not strictly apply but one can obtain estimates by applying similar considerations to that volume which can affect the output signal, that volume being determined by skin depth limitations corresponding to frequencies or times of interest. In order to obtain more accurate results for electrically large objects, and even for electrically small electric dipole objects (due to nonlinearities), one can try to perform more detailed calculations analytically and/or numerically. For calculations which include the detailed nonlinear and time varying characteristics of the source region one can try to simplify the problem somewhat by simplifying the object geometry, yet keeping the various important features of the object. Such idealized object geometries can be studied in nuclear source regions to form a set of canonical problems through which one can hope to understand and categorize the various detailed features of interaction in an EMP source region.