EMP From Chemical Explosions

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This paper is concerned with the emission of electromagnetic pulses from conventional chemical explosions. These explosions are to be contrasted with those due to nuclear sources and physical sources (nonnuclear without chemical reactions). The fact that such a pulse exists is often a surprise to some, yet the absence of a pulse should be more of a surprise. The open literature relating to the phenomena isn't extensive, and the subject hasn't been developed to the extent that a unified theory is accepted. Most of the experiments have involved small (a few kilograms) explosive charges, and usually the electric field strength is measured in the near or induction zone rather than in the far field.

The method of approach in this paper involves a three-fold separation: (1) a theoretical analysis of the EMP generation of the pulses; (2) pulse propagation and detection; and (3) a description of results from experiments available in the open literature. In particular, the following topics are treated: chemical explosives, general description and theory, time delays, polarization, spectrum, mass dependence, field strength and its radial dependence, propagation characteristics, detection sensors, and tunnel propagation.

Explosives

It seems apropos to begin this paper with a summary of relevant facts pertaining to explosives in general. Several references[1,2,3] were consulted for this section, although the most useful was the book by Bailey and Murray.[4]

A broad definition of an explosive is a substance, which when initiated, decomposes explosively with the evolution of heat and gas. For general applications, the explosive must be capable of performing work on its surroundings. This, in turn, depends upon the available energy and its efficiency in kinetic generation, plus the time rate at which the energy is released.

Now an explosion is somewhat different in definition from an explosive. A suitable description of an explosion is a sudden expansion of gases generally accompanied by an acoustic wave and mechanical effects. Explosions may be conveniently divided into three types: (1) physical explosions, (2) chemical explosions, and (3) nuclear explosions. Physical explosions are due to rapid expansion of gases without a chemical reaction; examples are a bursting balloon or the sudden vaporization of water. Chemical explosions are caused by a rapid exothermic chemical reaction, which produces a gas and results in heat transfer. Nuclear explosions are due to either or both nuclear fission or fusion, resulting in an extremely large amount of thermal energy, neutrons, and x-rays. In this case, the process is an energy release due to a mass change rather than a chemical reaction. The rest of the paper will deal entirely with chemical explosions.

The normal chemical reaction that occurs in an explosion is combustion. Fuel elements, such as carbon or hydrogen react with oxidizing elements such as oxygen or a halogen. The system is capable of producing large quantities of carbon dioxide, carbon monoxide, water, and nitrogen, along with considerable heat. The solid and liquid explosives (condensed explosives) contain the necessary oxidizer to allow the reaction to proceed in the absence of air, whereas, fuels such as wood and coal aren't capable of explosive reaction unless they are finely divided and exposed to oxygen. The effectiveness of an explosion is determined more by the time rate of change of released energy rather than the released energy itself.

An early example of an explosive is black powder, which undergoes a reaction resembling

$$4KNO_3 + 7C + S \rightarrow 3CO_2 + 3CO + 2N_2 + K_2CO_3 + K_2S \quad .$$

This reaction is somewhat inefficient because potassium carbonate and potassium sulfide are both solids. A more efficient reaction is illustrated by

$$25NH_4NO_3 + C_8H_{18} \rightarrow 8CO_2 + 59H_2O + 25N_2 \quad .$$

Reactions of common single explosive compounds are given in the following three equations:

Nitroglycerine: $4C_3H_5N_3O_9 \rightarrow 12CO_2 + 10H_2O + 6N_2 + O_2$

TNT: $2C_7H_5N_3O_6 \rightarrow 7CO + 5H_2O + 3N_2 + 7C$

RDX: $C_3H_6N_6O_6 \rightarrow 3CO + 3H_2O + 3N_2$.

The total amount of heat released in an explosion is called the "heat of explosion" (Q). Q is a useful performance parameter. The free expansion of the combustion products into the atmosphere is characteristic of a thermodynamic process at constant pressure. The thermodynamic parameters are defined only at equilibrium, so that the nonequilibrium process during the explosion isn't described by the usual thermodynamic parameters, including temperature. The relationship[5] needed is

$$TdS = nC_p dT - T\left(\frac{\partial V}{\partial T}\right)_p dP \quad .$$

By using the ideal gas law, PV = nRT, and the second law of thermodynamics, dS = dQ/T, this becomes

$$dQ = nc_p dT - VdP \quad .$$

For a constant pressure process, dP = 0, so the appropriate specific heat is that at constant pressure, as expected. This also shows the direct relation between Q and T (the "temperature of explosion").

On the other hand, for high explosives in a gun, the transformation is more like a constant volume process. Then

$$TdS = nc_v dT + T\left(\frac{\partial P}{\partial T}\right)_v dV$$

$$dQ = nc_v dT + PdV \quad .$$

At constant volume, $dV = 0$, and this also shows the direct relation between Q and T, although the specific heat is now c_v rather than c_p.

From a chemical viewpoint, the heat of explosion is the difference between the heat of formation of the explosion products and the heat of formation of the explosive compound.

The "temperature of explosion" is defined as the maximum temperature at which the gaseous products reach for an adiabatic process. This is a good performance parameter for an explosive. T typically ranges between 2500 and 5000 °C for military high explosives. From the above, T may be calculated from $dQ = ncdT$, where c is c_v or c_p, depending upon the situation. Thus,

$$\Delta T = \frac{Q}{\sum_i n_i c_i} \quad .$$

Clearly, higher temperatures are achieved when the product molecules are small, corresponding to small heat capacities.

The initiation of an explosion is generally by either burning or detonation. The burning process consists of a series of chemical reactions that occur at the instantaneous surface of the charge. The temperature of each inner layer adjacent to the burning zone is brought to the ignition point by heat transfer from the reaction zone. The reaction rate at which the surface recedes depends upon the time rate of heat transfer; this rate is quite slow compared with detonation.

Initiation by detonation requires a shock wave to pass through the explosive material. The shock may originate by burning. What happens here is that the flame surface accelerates until it becomes transformed into a shock wave. Another method is to use a shock wave from a small detonating charge. Very often, a burst of light is produced at the onset of detonation. Whereas in burning to detonation, the delay in actual detonation may be on the order of milliseconds, shock to detonation requires times measured in microseconds for typical masses. Often a high explosive is initiated by an explosive train that consists of an initiator (requiring a small energy input), which then activates a booster, which in turn initiates the main charge.

General Description and Theory

The emission of electromagnetic radiation from a chemical explosion is well established. A small number of published references are listed in this paper. In general, subsequent to detonation, an explosion produces an electromagnetic pulse (EMP). The spectrum and intensity are functions of such parameters as explosive type and particle size.[6] There appears to be a time delay between detonation and emission, which may depend upon the mass of the explosive and the ignition method. The polarization, field strength, and radial dependence depend partly upon the receiving sensor location. The proximity of the explosive to the earth's surface affects the signal. Often, two distinct pulses are recorded.[7] The first is directly associated with the explosion, whereas the second is probably dependent upon the height of the charge above ground. Keep in mind that the combustion products include heavy ionized atoms.[8] The ignition method also influences the signal.[9] For example, flame ignition of spherical charges lead to signals that differ from those initiated by an electric detonator.

There are several qualitative explanations of the EMP emission.[10] For example, one possibility mentioned in the literature is generation produced by electric sparks between detonation products and case fragments. Probably the major contribution originates in an asymmetric separation of the positive and negative ions from the high explosive products as a result of high temperature.[11-14] The asymmetry may originate in a number of ways such as the geometry of the immediate surroundings, current leads in electric detonation, and single point flame ignition. Recall that the generation of a dipole isn't sufficient for radiation; the dipole moment must have a nonzero second time derivative, which is equivalent to a nonzero first time derivative of the current.

It was previously mentioned that electric discharge between detonation fragments of opposite charge or different potential may initiate an EMP signal. The question is how these charges are separated, and how millions of volts can be generated in the process. Here's a brief explanation.[15] When two dissimilar materials are in contact, the system attempts to establish thermodynamic equilibrium, and it does this by maximizing entropy. It turns out that this is equivalent to matching temperature, pressure, and chemical potential in both materials. In particular, the attempt to equalize their chemical potentials requires the transfer of electrons from one to the other; incidentally, this is equivalent to matching Fermi levels in a transistor. Thus, the two substances become oppositely charged as a result of an approach to thermodynamic equilibrium.

The charge transfer causes a voltage difference between the two masses, but the magnitude is only on the order of a few tenths of a volt. How then can a simple charge separation, producing less than a volt, result in hundreds of thousands of volts? The answer is that work is done in separating the charges (such as mechanical work done by a person by lifting an insulated shoe off of a rug); only a minute amount of external work is required. The result is two oppositely charged materials with an extremely large voltage difference capable of producing an electrical discharge.

To expand upon the theory, consider the explosion to cause some of the detonation products to be charged, so that one (initially, at least) sees an expanding, accelerated, nonuniformly charged shell that produces electromagnetic radiation in the radio frequency portion of the spectrum.

Assume a single charge q moving with velocity v and acceleration $\dot{v}$ at a distance r from an arbitrary fixed origin. Let n be a unit vector from the instantaneous position of q to the observation point and θ be the angle between n and v. Recall that the electric field at r due to the moving charge is

$$E = \frac{q}{4\pi\varepsilon_0}\left[\frac{n - \frac{v}{c}}{\gamma^2\left(1 - \frac{v}{c}\cos\theta\right)^3 r^2}\right] + \frac{q}{4\pi\varepsilon_0 c}\left[\frac{n \times \left\{\left(n - \frac{v}{c}\right) \times \frac{\dot{v}}{c}\right\}}{\left(1 - \frac{v}{c}\cos\theta\right)^3 r}\right] \quad , \quad \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \quad .$$

The problem is nonrelativistic such that $v/c \ll 1$. Then E reduces to

$$E = \frac{q}{4\pi\varepsilon_0 r^2} n + \frac{q}{4\pi\varepsilon_0 c^2 r}[n \times (n \times \dot{v})] \quad ,$$

$$B = \frac{1}{c} n \times E \quad ,$$

and

$$H = \sqrt{\frac{\varepsilon_0}{\mu_0}}(n \times E) \quad .$$

Notice that this expression is velocity independent. The second term in E is the part that contributes to radiation, and is a function of q, r, and the acceleration.

Let's assume that the explosion produces a charge separation such that some of the particles composing the cloud are charged, subject to the constraint, $\Sigma q_i = 0$. The net radiated E field due to the expanding cloud will be the (vector) sum of the individual fields,

$$E = \frac{1}{4\pi\varepsilon_0 c^2} \sum \frac{n_i \times (n_i \times q_i \dot{v}_i)}{r_i} \quad .$$

There are several possibilities for this to be zero. For example, constant acceleration in a spherically symmetric expanding cloud of like charge gives E = 0, as would constant velocity for any configuration. In practice, the symmetry will most likely be broken due to any or all of several reasons such as nonuniform radial acceleration, asymmetric charge distribution over the shell, nonspherical shell shape, etc. Thus, one expects a nonzero, time dependent E and B field in the radio frequency region of the electromagnetic spectrum.

An equivalent approach to the problem is to view the expanding cloud as a time and position dependent charge and current distribution and calculate the fields at the observation position. A Taylor series expansion of the resulting integrals can be interpreted as a superposition of multipoles of various orders, of which the above expression for E comes from the dipole term. Yet, this can be somewhat misleading. Assume τ to be a characteristic period or time interval for any appreciable change in the clouds charge distribution. Then the system has frequencies on the order of $1/\tau$, corresponding to wavelengths $\lambda \sim c\tau$. Suppose a characteristic length (or diameter) of the cloud to be ℓ, then for dipole radiation, the propagation time across the system, ℓ/c should be short compared to r. That is,

$$\ell / c << \tau \sim \frac{\lambda}{c} \quad ,$$

so that this is equivalent to $\ell << \lambda$. Thus, for dipole radiation (not a necessity for the present analysis), $\ell << \lambda << r$. There are no problems with $r >> \lambda$ and ℓ, but $\ell << \lambda$ may seem questionable. Yet consider the following: the time r is on the order of ℓ / v, where v is a typical particle speed, then $\ell << \lambda$ is equivalent to $v\tau << \frac{c}{v} = c\tau$ or $v << c$, which is certainly the case for the cloud. Thus dipole radiation is probably a valid assumption, and this aspect is pursued by Wouters.[17]

Time Delay

One of the consistent points made in the literature for EMP from chemical explosions is that a time delay exists between detonation and the appearance of the electromagnetic pulse. The explanation is only speculative, although Cook[18] suggests that the delay corresponds to the time for the hot gas to strike the ground. Several references suggest delays between detonation and pulse appearance to be approximately 50 μs, 80-160 μs, and 300-600 μs, respectively.[19-21] One set of results[22] gave a 100-200 μs delay after case fragmentation with signals occurring even after 1 ms. A uranium cased HE charge resulted in a 33-40 ms delay. Wouters[23] reports two pulses, the first with about 200 to 500 μs delay lasting for 700 μs and a second with 2 to 5 ms delay lasting for 10 ms. A more extreme case[24] showed a 2 s delay between firing and the peak signal, and some signals lasted greater than 15 s; the detection was at extremely low frequency near 1 Hz. Boronin[25] suggests a few millisecond delay and speculates that the delay is proportional to the cube root of the charge mass.

Polarization

There appears to be very little discussion relative to polarization of the pulse. Takakura and Cook separately suppose the wave to be unpolarized as determined from their experiments. Yet, Wouters lists a vertical polarization. From a theoretical viewpoint, a time dependent vertical dipole would be expected for an explosive mass on or near the earth's surface. The reason for this is that the charged cloud will expand in a very asymmetric fashion due to the surface; this would result in a vertical dipole. In a spherical coordinate system with the vertical being the polar or z axis, the dipole moment would be vertical, and this results in nonzero r and θ components of the electric field but little ϕ (horizontal) component. Near the explosion, the radial component would be quite strong, but as r increases, E_r should rapidly decrease, leaving only E_ϕ to form the radiated field. Note that on or near the earth's surface, E_θ corresponds to vertical polarization. Thus, at a radial distance several wavelengths away, a receiving antenna should be vertically polarized. There is a second reason for this polarization, which will be mentioned in the section on radial dependence.

Spectrum

What little information is available on the spectrum and pulse shape is sparse and inconsistent. Frequencies quoted range from about 1 Hz to an excess of 100 Hz. One source states that, over a limited range, the dominant frequency appears to decrease with increasing explosive mass. It's very likely that the spectrum is highly dependent upon initiation time. For example, if a flame ignition were used, one would expect the spectrum to be more concentrated in lower frequencies as compared to rapid detonation with a short rise time. In addition to initiation method and type of charge, even the immediate environment could easily affect both the spectrum and pulse shape. If so, a unique signature for a given explosive type may not exist.

Explosive Mass Dependence

It was previously mentioned that over a limited range, there is some inconclusive evidence that the time delay between detonation and the appearance of EMP is proportional to the cube root of the explosive mass. There is further evidence of a functional dependence of the electric field strength on the mass.[26] A statistical analysis of an excess of 100 experiments at various distances from several different charge masses shows that the magnitude of the electric field is directly proportional to the explosive mass.

Radial Dependence

The source of the EMP is clearly the explosive mass. The question of the pulse propagation characteristics is a subject in electromagnetic theory, which will be pursued here in an abridged manner. Even though the charge and current densities are unknown, this doesn't prevent an analysis in a generalized sense.

The radiated fields may be derived from the solution of the inhomogeneous wave equation for the scalar and vector potentials,

$$\nabla^2\phi - \varepsilon\mu\ddot{\phi} = -\frac{1}{\varepsilon}\rho \quad ,$$

$$\nabla^2 \mathrm{A} - \varepsilon\mu\ddot{\mathrm{A}} = -\mu \mathrm{J} \quad .$$

The vector and scalar potentials are connected through the Lorentz gage.

$$\nabla \cdot \mathrm{A} + \varepsilon\mu\dot{\phi} = 0 \quad ,$$

whereas the charge and current densities are connected through the equation of continuity,

$$\nabla \cdot \mathrm{J} + \dot{\rho} = 0 \quad .$$

The solutions for the two wave equations are

$$\phi(\mathrm{r,t}) = \frac{1}{4\pi\varepsilon}\int \frac{\rho(\mathrm{r',t'})}{|\mathrm{r}-\mathrm{r'}|}\,\mathrm{dV'} \quad ,$$

$$\mathrm{A(r,t)} = \frac{\mu}{4\pi}\int \frac{\mathrm{J(r',t')}}{|\mathrm{r}-\mathrm{r'}|}\,\mathrm{dV'} \quad ,$$

where t′ is the retarded time, $t-\frac{1}{c}|r-r'|$, r is the field position, r′ is the source position where dV′ is located. From these solutions, the electric and magnetic fields are found from

$$\mathrm{E} = -\nabla\phi - \dot{\mathrm{A}} \quad , \quad \mathrm{B} = \nabla\times\mathrm{A} \quad .$$

The reason for displaying the integrals for ϕ and A is to point out that the denominator, $|r-r'|^{-1}$, may be expanded in a Taylor series, and each term may be integrated separately. This results in a multipole expansion of the time dependent source, producing dipoles plus quadrupoles, plus octapoles, etc. All of those moments are time dependent. Normally, the lowest order, nonzero moment dominates. If the total charge is zero, then the monopole is zero, so one would expect the dipole to be the most important. For example, the frequency domain fields generated by an instantaneous electric dipole of moment p(t) and propagation number $k = 2\pi/\lambda$ are

$$\mathrm{E_r} = -\frac{\mathrm{pk}^3}{2\pi\varepsilon}\cos\theta\left[\frac{\mathrm{i}}{(\mathrm{kr})^2}-\frac{1}{(\mathrm{kr})^3}\right]e^{\mathrm{i(kr}-\omega\mathrm{t)}}$$

$$\mathrm{E}_\theta = \frac{\mathrm{pk}^3}{4\pi\varepsilon}\sin\theta\left[\frac{1}{(\mathrm{kr})^3}-\frac{\mathrm{i}}{(\mathrm{kr})^2}-\frac{1}{\mathrm{kr}}\right]e^{\mathrm{i(kr}-\omega\mathrm{t)}}$$

$$\mathrm{H}_\phi = -\frac{\omega\mathrm{pk}^2}{4\pi}\sin\theta\left[\frac{\mathrm{i}}{(\mathrm{kr})^2}+\frac{1}{\mathrm{kr}}\right]e^{\mathrm{i(kr}-\omega\mathrm{t)}} \quad .$$

These fields may be interpreted in terms of three zones: static, induction, and far.

(1) Static zone: $D \ll r \ll \lambda$, or sometimes taken as $r < \lambda/200$. Basically, the field point is so close to the source, in terms of wavelength, that the instantaneous field may be calculated from the static equations. E varies as $1/r^3$.

(2) Induction zone: $D << r \sim \lambda$. Both E and H vary as $1/r^2$, and are $\pi/2$ out of phase with the static zone field.

(3) Far field: $D << \lambda << r$. The field point is large compared with both wavelength and radiator size. Both E and H vary as $1/r$ and are $\pi/2$ out of phase with the induction zone. These are the dipole fields that radiate.

These expressions presuppose that the source size is much smaller than both the wavelength and distance to the field point. Thus, one may consider the source at the explosive mass to be a time dependent superposition of several multipole moments.

A second characterization of the field zones is in terms of three radial regions chosen to correspond to both antenna theory and diffraction theory. A direct solution of the integrals for ϕ and A may be described in terms of these zones, depending upon wavelength and D, the largest dimension of the explosive charge, with D assumed greater than λ.

(1) Reactive near field region: Commonly taken as the circular zone for which

$$r \leq \frac{2}{\pi}\sqrt{\frac{D^3}{\lambda}} \quad .$$

In this region, the reactive component of the field predominates.

(2) Radiating near field (Fresnel) region: This is a circular zone within the limits

$$\frac{2}{\pi}\sqrt{\frac{D^3}{\lambda}} \leq r \leq \frac{2D^2}{\lambda} \quad .$$

In this zone, the radiation fields predominate, but the antenna radiation pattern is a function of radial distance.

(3) Far field (Fraunhofer) region: This zone extends from $r = 2D^2/\lambda$ to infinity. The field components are transverse and the radiation pattern is independent of r.

The discussion of a multipole expansion explains why so many different experimenters don't agree on the radial dependence of the field strength. Various reports cite the functional dependence upon r as $1/r$, $1/r^2$, and $1/r^3$. For those measurements that satisfy $r >> \lambda >> D$, then the dependence is $1/r$, as is usually measured. For the case where $\lambda >> r >> D$ (static zone), then the dependence is $1/r^3$; this is often quoted in the literature. For those who made measurements in the induction zone ($r \sim \lambda >> D$), the dominant dependence is $1/r^2$, with significant contributions from the $1/r^3$ and $1/r$ terms, which complicates the analysis.

In general, interpretation is best made in the far zone, although a trade-off is made in that the field strength is lower. Yet, it's obvious that the far zone is where military and intelligence detection would be most useful; this includes nuclear versus chemical nonproliferation studies.

Field Strength

One would like to know what to expect for field strength from a chemical explosion. A search of the literature shows the electric field strength to vary from about 10^5 V/m in the source to nearly zero close but outside the source. It doesn't take much thought to realize that E will vary with distance (treated above), with explosive mass (treated in the section on mass dependence), type of detonation, polarization of the receiving antenna, frequency bandwidth of the receiving system, etc. The mass and distance dependence are simple. Polarization has been treated. The type of detonation partly determines the rise time, hence the frequency spectrum. In general, all of those parameters are understood, at least qualitatively.

Propagation Characteristics and Ground Influence

A pulse originating at the chemical explosion travels to a receiving sensor by three modes: ground wave, tropospheric wave, and sky wave, although the latter is of minor importance for most applications. Those terms are all defined and explained in this section.

Propagation Terminology

The propagation modes between two points may be divided several different ways; there is no unique, universally accepted terminology. The following division will be pursued in this section.

Sky wave: electromagnetic radiation refracted back to the earth from the ionosphere.

Ground wave: A surface wave in contact with the ground, which travels along the earth's surface.

Direct or space wave: A wave propagating directly from the source to the receiving point.

Ground reflected wave: A wave propagating from the source to the receiving point via a ground reflection.

Tropospheric wave: The superposition of a direct wave and a ground reflected wave plus other possible modes such as tropospheric scattering and diffraction due to obstacles, but excluding a sky wave.

Ground Wave

A ground wave travels directly along the ground and terminates on the earth's surface. Because the earth typically has semiconductor characteristics, the ground wave is rapidly attenuated. Over sea water, the attenuation is much less than over land and decreases as frequency is decreased. As a rule of thumb, ground wave propagation for communication purposes becomes quite difficult over land for frequencies above about 3 MHz.

Ground wave propagation over a conducting surface can be treated exactly by using the Maxwell equations. That approach would not be appropriate for this report, therefore, a summary will be presented.

First consider propagation parallel to a surface separating a perfect conductor and a dielectric such as air. The electric field is normal to the conductor, whereas the magnetic field is parallel. The energy flow is then directed perpendicular to both the E and H fields. A surface current flows in the propagation direction, and a surface charge appears, equal in magnitude to the normal component of the displacement vector at the surface.

When the conductivity is reduced to finite values, several important modifications occur. The main effect is the appearance of a small tangential component of E in the propagation direction. This causes an additional current to account for energy losses. Note that this tangential E produces a normal component of the Poynting vector, corresponding to a small propagation into the conductor. The finite conductivity also means that the fields are no longer zero in the conductor as they are for infinite conductivity.

In the dielectric, the E field is nearly perpendicular to the surface for a good conductor, but it has a forward tilt. It's elliptically polarized in the propagation plane. Inside the conductor, the E field is again elliptically polarized and is nearly parallel to the surface.

The important region for EMP reception is the dielectric. In addition to the forward tilt of the electric field, the magnitude of E drops off in the direction along a wave front away from the surface. Thus the energy density is concentrated in the vicinity of the conductor. The phase velocity is less than the speed of light in the dielectric due to the presence of the conductor, so that the component of the velocity parallel to the surface corresponds to a slow wave. The forward tilt of the E field increases as the conductivity decreases and the frequency increases.

The importance of this discussion on ground waves lies in EMP detection in the vicinity of the chemical explosion.

Direct Plus Ground Reflected Wave

Suppose the source and receiving antenna are elevated above the ground by at least a half wavelength. Unless the receiving point is beyond the horizon, the net field will be the vector sum of the direct wave plus the ground reflected wave. Thus, one should expect an interference effect depending upon source and receiving heights, wavelength, and ground properties. An assumption is made that the receiving point is in the far field such that both E and H have a free space dependence of 1/r.

There will be interference between the two waves because of the difference in path lengths. The magnitude of the interference is partially determined by the phase shift of the ground reflected wave upon reflection. This, in turn, depends upon ground dielectric constant and conductivity. At nearly grazing incidence the phase shift is nearly 180 degrees. If the optical path length difference is calculated and the two waves are superimposed, the resultant electric field at a distance r from the source is

$$E \approx \frac{2E_0}{r} \sin \frac{2\pi hH}{\lambda r} ,$$

where h is the source height, H is the receiving antenna height, and E_0 is the amplitude of the source. At nearly grazing incidence (typical case) the sine may be replaced by the angle, which gives

$$E \approx E_0 \frac{4\pi hH}{\lambda r^2} .$$

Note the following characteristics of the interference. Whereas the typical far field E and H vectors vary inversely as the first power of distance, the interference produces an inverse square dependence on each, so that the intensity drops off as $1/r^4$. This is a rapid decrease, so that one should not expect to detect a high frequency EMP signal via tropospheric propagation much beyond the horizon. Also, note that the field strength is a periodic function of both source and receiving height, or at grazing incidence, linearly proportional to the product of the heights. For EMP detection, the source height may be uncontrollable, but the receiving antenna height is generally at the experimenter's disposal.

Atmospheric Refraction

Over the horizon propagation is possible due to atmospheric refraction. Under normal conditions, the tropospheric index of refraction decreases with altitude, so that a ray will be bent towards the earth. This effect is enhanced in the presence of a temperature inversion. Recall that the tropospheric temperature usually decreases with height, yet some atmospheric conditions reverse this gradient such that temperature increases with height over a limited range. This range over which dT/dz is positive is called a temperature inversion. The meteorological causes of an inversion are not important for the purposes of the report, but major reasons will be mentioned. The first is a radiation inversion that occurs at the earth's surface as a result of a higher rate of heat loss near the surface as compared to upper heights. The second is a dynamic inversion that is associated with frontal motions of air masses. The important point relative to EMP propagation is that the temperature inversion creates a further decrease in index of refraction with height so that tropospheric refraction is enhanced. This then implies an increased propagation distance.

Ducts

A duct may be considered as an extreme case of atmospheric refraction treated in the previous section. The actual bending of the waves is primarily due to the gradient of the refractive index. If an abrupt change in the index occurs at a particular height, then the phenomenon is more like reflection than refraction. It should be stated here that the water vapor content of the atmosphere has a greater effect on the index of refraction than temperature, so that the gradient of both water vapor density and temperature determine the extent of any refraction.

If at some height, a sharp change occurs in the refractive index that persists in time, then a duct is formed in which waves may be partially trapped in the nature of a leaky waveguide. If the lower side is the earth, a surface duct is formed. If the lower surface is due to an upper temperature inversion, it's called an elevated duct.

Ducts are more likely to form over water, and they typically vary from a few meters to several hundred meters in thickness. Because of the waveguide nature of ducts, an approximate cutoff frequency exists, below which no propagation occurs.

Thus the duct acts like a high pass filter. In practice, the propagated frequencies are limited typically to fall in the range of approximately 50 to 450 MHz.

Diffraction

One of the properties of an electromagnetic wave is that its propagation direction is modified by the presence of material objects such as hills, buildings, trees, etc. The phenomena of diffraction is similar to scattering; the subtle difference isn't apropos to this report. The extent of diffraction is mainly a function of a ratio consisting of a typical transverse dimension to the incident wavelength. When the ratio is large, such as visible light striking a basketball, there is very little diffraction. When the ratio is small, such as a radio wave striking a basketball, a large amount of diffraction occurs. The same results are obtained if an obstacle is replaced by an opening of the same size and shape.

The importance of diffraction for EMP reception occurs when reception is via a tropospheric or ground wave that may encounter a structure or a hill. Depending upon the wavelength being sensed, the placement of a receiving antenna should be located at an expected maximum of the diffraction pattern. This presupposes the experimenter is familiar with diffraction theory sufficiently well to estimate the pattern.

Sensors

The sensors used for EMP detection may be described in four classifications: antennas, current monitor transformers, B-dot (or surface current) probes, and D-dot (or surface charge) probes. Of these four, antennas are the most important, because they may be placed anywhere, whereas the other three require transmission lines or metallic surfaces. Each of the four classifications may be subdivided into various types; this is especially true of antennas. One should also note that B-dot and D-dot measurements (at the same point) are not independent, because they're coupled through the equation of continuity. What follows is a brief description of the four types.

B-Dot Detectors. The purpose of a B-dot detector is to measure the time derivative of the tangential component of the magnetic field at the surface of a conductor. This is equivalent to measuring time rate of change of the surface current per unit length, where the unit length is perpendicular to the current.

The particular B-dot detector used by LANL is a Prodyn Model B-S50, which consists of a half-cylinder loop on a base plate. The internal configuration is designed to be insensitive to the displacement current, so that only the magnetic field is sensed. It has the following characteristics: rise time of 0.5 ns, high frequency 3 dB drop-off of 700 MHz, and equivalent area of 0.001 m^2.

The basic theory of the device follows from the curl E Maxwell equation

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad ,$$

where the symbols have the usual meaning. If both sides are multiplied by an element of surface area, dA, and integrated over the area of the B-dot loop, one obtains

$$\int (\nabla \times E) \cdot dA = \int \frac{\partial B}{\partial t} \cdot dA \quad .$$

The surface integral of curl E may be converted to a line integral around the loop perimeter, which then gives the output voltage of the sensor. That is, because

$$\int (\nabla \times E) \cdot dA = \oint E \cdot dL \quad ,$$

and the right-hand side is voltage (by definition),

$$V = -\int \frac{\partial B}{\partial t} \cdot dA \quad .$$

Because the equivalent area is fixed in space and time,

$$V = A \cdot \frac{\partial B}{\partial t} \quad ,$$

which clearly shows that the output voltage is proportional to the time derivative of the magnetic induction vector (hence, the name, B-dot). Thus, the time integral of the output voltage gives the tangential component of the magnetic field.

The surface current in a given direction can also be obtained from the output voltage in the following manner. Recall that the boundary condition on tangential H is that its discontinuity at a perfectly conducting surface is equal to the current density per unit length, K. Then

$$V = A \cdot \frac{\partial B}{\partial t} = A\dot{B}\cos\phi \quad ,$$

where ϕ is the angle between the vector area A and $\partial B / \partial t$. Now $B = \mu H$, $|H| = |K|$, and $\cos\phi = \cos\phi\left(\theta + \frac{\pi}{2}\right) = -\sin\theta$, where θ is the angle between the surface current and the vector area. So,

$$V = A\dot{B}\cos\phi = -\mu A\dot{K}\sin\theta \quad .$$

From this, the time integral of the output voltage also can give the surface current in a given direction.

D-Dot Detectors. The D-dot detectors measure the time derivative of the normal component of the electric field at the surface of a conductor. This is equivalent to measuring the time rate of change of the surface charge density.

The particular D-dot detector used by LANL is a Prodyn Model SD-S30, which consists of a hemispherical dome supported above a metal mounting surface with a dielectric ring separating the two. It has the following characteristics: rise time of 1 ns, high frequency 3 dB dropoff of 350 MHz, equivalent area of 0.01 m^2.

The basic theory follows from the fact that the displacement current, $\dot{D}$, is equivalent to a current density, J, so that $J = \dot{D}$. Because J is current per unit area, $I = A\dot{D}$. On the other hand, the discontinuity of normal D at the surface of a perfect conductor is the surface charge density, σ. Thus, $I = A\dot{\sigma}$. Then the output voltage is given by

$$V = IR = RA\dot{\sigma} = RA\varepsilon\dot{E} \quad .$$

Therefore, both the normal component of the electric field at the surface and the surface charge density may be found by the time integral of the output voltage.

Note that the output of a D-dot and a B-dot detector at the same point are not independent because J and ρ or K and σ are connected through the equation of continuity

$$\nabla \cdot J + \frac{\partial \rho}{\partial t} = 0 \qquad \text{(in a volume)}$$

$$\nabla \cdot K + \frac{\partial \sigma}{\partial t} = 0 \qquad \text{(on a surface).}$$

Current Monitor Transformers. The purpose of a current transformer (sometimes called a coil), is to measure total (algebraic) current on a conductor threading through the sensor. Like the B-dot detector, it actually senses magnetic field, not current, even though the output results in a voltage that may drive a current through a load.

The sensor consists of a toroid core of high permeability material, around which a coil is wound. Thus, it resembles an iron doughnut with a coil of wire wound in the theta direction. If a time dependent current flows through the toroid hole, the magnetic field of the former threads through the coil and induces a voltage at the output. Thus, the probe is similar to a transformer in which the primary is a single turn conductor and a secondary consisting of the coil. As used for EMP, the sensor measures surface wave sheath currents on the outer surface of a coaxial cable, and common mode currents on power lines and phone lines.

The particular coil used by LANL is a Pearson current monitor transformer, Model 110, with the following characteristics: transfer impedance of 0.1 volt/amp, rise time of 20 ns, upper frequency dropoff of 35 MHz. The unit is completely enclosed in an electrostatic shield.

It should be noted that the output is proportional to the total current (or magnetic field) and not to their time derivatives. This is because of the large permeable core that causes the inductive reactance to be much larger than the resistance. This is easy to demonstrate.

Consider an equivalent series L-R circuit with the voltage input being a time-dependent magnetic field threading perpendicular through the coil of area A

$$L\frac{dI}{dt} + IR = A\frac{dB}{dt} = \mu\frac{dH}{dt}A \quad .$$

Because $X_L >> R$, this reduces to

$$L\frac{dI}{dt} \approx \mu A\frac{dH}{dt} \quad .$$

Thus, $I = \mu AH/L$, which shows that the current depends upon the magnetic field rather than its time rate of change.

Antennas. Whereas the sensors previously described were placed on cables or conducting surfaces, antennas may be located anywhere. Furthermore, there's a wide choice in type and size of antennas, so that one has considerable flexibility in choosing the type best suited for measuring a particular parameter. Note that the vast majority of antenna literature pertains to monochromatic, steady-state signals; that is, nearly every treatment of antennas assumes an $\exp(j\omega t)$ time dependence. Clearly that's not the case with a fast transient as experienced in EMP. The pulse response of an antenna differs from its steady-state condition. Nevertheless, it appears that an approximate description in terms of steady-state theory is appropriate for guidelines. What follows is such a treatment.

1. Dipole. A dipole antenna, as commonly termed, consists of a conductor of length L, split at the center and fed by a transmission line; it may be vertically or horizontally polarized. This is often called a center fed dipole. The free-field radiation pattern for a center-fed antenna supporting an integral number of half wavelengths with a sinusoidal current distribution is

$$E = \frac{60I}{r}\left[\frac{\cos\left(\frac{\pi L}{\lambda}\cos\theta\right) - \cos\frac{\pi L}{\lambda}}{\sin\theta}\right] ,$$

where the symbols have the usual meaning. The half-wave dipole is of particular interest ($L/\lambda = 1/2$),

$$E = \frac{60I}{r}\,\frac{\cos\left(\frac{\pi}{2}\cos\theta\right)}{\sin\theta} .$$

This produces the familiar figure eight radiation pattern such that the maximum lies perpendicular to the antenna, and a null exists off the ends.

In practice, the radiation pattern is modified by ground reflection. This is a complex situation because the interaction depends upon antenna height, frequency, ground conductivity, and dielectric constant. For example, as the antenna height decreases, the pattern deteriorates to a more omnidirectional radiator with significant radiation off the ends. Furthermore, the input impedance is a function of height due to ground reflections.

2. *Monopole.* The monopole consists of a quarter wavelength, vertical conductor fed at its base, usually by the center conductor of a coaxial cable with the outer conductor being grounded. Thus, the earth serves as an image conductor, in which case, the monopole acts as a vertically polarized dipole with an omnidirectional radiation pattern in the horizontal plane.

The monopoles consist of a vertical rod with eight radials sloped down from the horizontal at 45 degrees. The reason for the slope on the radials is to more closely match the 50-ohm impedance of the coaxial cables feeding the antenna. If the radials were horizontal, the impedance would be more like 30 ohms. These antennas have been the workhorses for the EMP project.

3. *Yagi.* The dipole serves as the building block for a beam antenna consisting of a parasitic array. Here, one element is driven and one or more elements are mutually coupled. In transmission, the current in the driven element induces currents in the parasitic elements, which in turn, contribute to the total radiation pattern. A typical three-element Yagi has a gain of about 9.7 dB over an isotropic radiator.

4. *Log Periodic.* The dipole also serves as the basis for the pseudo frequency independent antenna known as a log periodic. This is a parallel arrangement of center-fed half-wavelength dipoles, which are fed 180 degrees out of phase. The dipole lengths increase along the antenna, so that the included angle is a constant, and the lengths (L) and spacings (S) of adjacent elements are scaled such that

$$\frac{S_{n+1}}{S_n} = \frac{L_{n+1}}{L_n} = \text{constant}.$$

The most efficient radiation and reception occurs at that element that corresponds to $\lambda/2$. The longer element behind the half-wavelength element serves approximately as a reflector, whereas the shorter element immediately in front acts like a director. Other elements are not of the proper length to be in resonance. The bandwidth of the antenna is roughly bounded by wavelengths equal to twice the dipole lengths at the two extreme ends.

(5) Slot. A slot antenna consists of a metal sheet in which a slot of length $\lambda/2$ and width much less than λ is cut. It's fed by a transmission line typically at the center points of the slot. Currents occur as a distribution over the metal plate, and radiation occurs from both sides of the sheet. It acts just like its complementary antenna (dipole

whose dimensions are identical to the open slot) except that the polarization is rotated by ninety degrees. For example, a horizontal slot is equivalent to a vertically polarized dipole.

The terminal impedance of the slot (Z_s) is related to that of the complementary dipole (Z_d) in the following way:

$$Z_s = \frac{Z_0^2}{4Z_d} = \frac{35480}{Z_d} \text{ ohms.}$$

With a typical dipole impedance of 73 ohms, this means that the slot has an input impedance close to 500 ohms. In order to match this impedance to an ordinary coaxial cable, the feed point may be moved closer to one end, perhaps a distance of $\lambda/20$ from an end.

(6) Bicone. The bicone is an antenna that consists of two identical cones opening in opposite directions with a common axis. The outstanding characteristic is the broadband feature. The antenna is fed by a transmission line at the apex of each cone. The electric field has only a θ component, whereas the magnetic field is in the ϕ direction. Thus, the surface current moves along a generator of the cone much as if it were a dipole of nonzero and variable thickness. Because of E_θ and H_ϕ, the Poynting vector is in the radial direction in the form of a spherical wave. Also, E_θ and H_ϕ allow the current and voltage at the terminals to be determined, which in turn, gives the input impedance, Z.

$$Z = 120 \, \mathrm{Ln} \cot \frac{\alpha}{4} \quad ,$$

where α is the total conical angle. Because of size and mechanical considerations, the bicone is most useful at high frequencies, perhaps above 100 MHz.

(7) Helix. The helical antenna is a wire wound helix with a ground plane placed at, and insulated from, one end. The antenna is fed between the ground plane and the close end of the helix. Several distinct advantages are evident with the helix. The most important for pulse reception is that it's a traveling wave antenna, as contrasted to the usual resonant types. Thus, it doesn't require a series of reflections (for a given frequency) for its operation; there is no transient approach to steady state. It has a high gain and large bandwidth; in fact, the helix acts like a lens that refracts (bends) the incoming waves into itself from an effective aperture that is larger than its own cross-

sectional area. It's also evident that the helix is basically polarization independent, which is a great advantage for EMP measurements. The disadvantage is similar to that of the bicone, namely, size and mechanical considerations.

(8) Beverage. The Beverage antenna is an excellent example of a traveling wave antenna. It consists of a wire strung parallel to the ground with the far end (towards the source) terminated in the characteristic impedance of the wire-ground system. The sensor functions because the earth has finite conductivity; an infinite conductivity would produce null results. The explanation is that, because of the finite conductivity, there's a forward tilt of the vertically polarized electric field, so that the horizontal component induces a current that travels in phase with the wave towards the receiver. That portion of the wave that is reflected at the receiving end is absorbed in the impedance at the other end. Hence, the antenna doesn't depend upon resonance (or the existence of a standing wave) and therefore shows much less distortion and dispersion for an incident pulse. In addition, it has a high directivity and is especially efficient at low frequencies (kHz and low MHz).

Propagation Through a Tunnel

In order for an electromagnetic pulse to propagate through a tunnel, it first must be coupled from the device to the tunnel. This problem partly depends upon the nature of the emplacement. For example, suppose the explosive is placed in an excavated cavity with one or more connecting tunnels. During, and for some time following the explosion, a time-dependent electromagnetic field is established in the cavity. The cavity size and shape, plus the device location play a major role in determining the EMP frequency spectrum.

The coupling problem consists of extracting a portion of the energy from the cavity via a tunnel. Clearly the tunnel has its own natural modes, and these are excited to an extent depending upon the electric and magnetic field orientations at the tunnel-cavity interface at any instant of time. A quantitative analysis of this coupling isn't within the scope of this paper. Nevertheless, it's clear that any arbitrary opening to the cavity will allow an electromagnetic pulse to enter. If there are conductors, such as cables or railroad tracks in the tunnel, the mode distribution is modified to include the possible existence of the extremely important transverse electromagnetic mode (TEM), which isn't possible in the absence of a conductor isolated from the tunnel walls.

This section is subdivided into three parts: waveguide modes, surface wave, and coax modes.

Waveguide Modes. A waveguide mode (non-TEM) may be propagated through a tunnel for all wavelengths less than approximately twice the largest transverse dimension. Wavelengths larger than this cutoff value are not propagated and therefore do not transport energy. All of the propagated modes are lossy modes because at the tunnel boundary, part of the energy is reflected and part is refracted into the surrounding medium. The refracted portion constitutes energy extracted from the wave and hence corresponds to a loss. Furthermore, the medium has a nonzero conductivity that enhances the loss.

Note that a tunnel is much like an inverse dielectric rod guide or optical fiber.[27] The rod and fiber guide internal waves, because the interior phase velocity is less than the velocity outside, hence a focusing effect. On the other hand, the velocity in the tunnel is larger than in the surrounding medium, so that a defocusing effect takes place.

While it's obvious that wall conductivity contributes to losses, there are two more subtle effects that also increase attenuation: wall roughness and wall tilt.[28] Roughness refers to local variations in the wall surface level relative to the average level. It turns out that the approximate dB loss due to roughness varies as the inverse fourth power of a typical transverse dimension and directly as the first power of the wavelength.

Just as roughness affects attenuation, so does long range tilt of the tunnel walls. This is because tilt causes mode conversion. The dB loss due to tilt is approximately proportional to the square of the tilt angle (for small tilt) and inversely proportional to the first power of the wavelength. Note that tilt is more important at high frequencies, whereas roughness contributes mostly at low frequencies.

Before leaving the waveguide mode, a few comments on coupling to a cross tunnel are apropos. Experiments[29] show that the signal strength decreases drastically in a cross tunnel (as intuitively expected) and it is independent of polarization (or antenna orientation). The reason for the weak coupling to cross tunnels is that the wave in the main tunnel propagates approximately in a geometrical optics fashion and is therefore almost unaffected by any cross tunnel openings. On the other hand, the higher order (or scattered) modes have a wider angular range and therefore couple more efficiently than the primary mode. Because these modes are largely unpolarized, the lack of polarization, as observed experimentally, is explained.

Surface Waves. The previous section has treated tunnel propagation in the absence of conductors threading parallel to the walls. In practice, there are normally power lines, telephone lines, coax cables, pipes, railroad tracks, etc., which render the analysis to be more complicated. Yet, the very presence of a longitudinal conductor makes possible the existence of a TEM, with no cutoff frequency. In addition, a conductor parallel to the walls can support a surface wave, both of the Sommerfeld and Goubau types, which is the subject of this section.

(1) *Definition.* One may define a surface wave as a wave propagating along an interface between two different media without radiation.[30] A surface wave is bound to a surface, and radiation occurs only at curvatures, nonuniformities, and discontinuities. Note that it isn't a leaky wave, which would exhibit a continuous radiation process. Thus, the Poynting vector is not quite parallel to the surface but has a small component directed into the bounding medium. This tends to keep the energy concentrated near the surface.[31] From a mathematical viewpoint, surface waves are particular solutions of the wave equation where homogeneous or stratified media are separated by plane or cylindrical surfaces.[32]

(2) *Properties.* The main characteristics of a surface wave are that its phase velocity is typically less than that in the surrounding medium and that the field strength decreases over a wavefront as one recedes from the surface; this is characteristic of a inhomogeneous wave such as is experienced in total internal reflection.[33,34] Thus, the energy density decreases away from the surface. The interface must be straight in the propagation direction, but it can take a variety of forms in the transverse direction.[35]

(3) *Two Types.* There are two types of surface waves, which we'll call Sommerfeld and Goubau, respectively. The Sommerfeld wave is bounded by virtue of the finite conductivity of the conductor, so that the Poynting vector has a component directed into the surface. The field extension is very large. The Goubau wave is bound by a dielectric-coating and/or a surface modification (such as a corrugated outer conductor of coaxial cable). Whereas finite conductivity is a requirement for the existence of a Sommerfeld wave, it's not required for the Goubau wave. In general, the field extension is less for the Goubau wave compared with the Sommerfeld; hence, the energy density is more concentrated near the surface in the former.

(4) *Sommerfeld Wave.* The Sommerfeld wave considered here consists of a wave supported by a circular cylindrical conductor embedded in a homogeneous dielectric (air, for example). The Sommerfeld solution consists of a radially symmetric transverse magnetic (TM) wave.[36] Asymmetrical modes also

exist, but they are very quickly damped out.[37] The wave equation is solved for both inside and outside the cylinder, and the boundary conditions are met by imposing the continuity of tangential E and H at the surface. Inside, the solution is in terms of Bessel functions, whereas outside, Hankel functions must be used. As expected, the phase velocity normally becomes less than the velocity of a free wave in the surrounding dielectric. An important result is that, although the field extends to infinity in the radial direction, the energy density tends to concentrate closer to the wire as the frequency increases and as the wire diameter decreases.

The electric field structure is interesting. Inside the cylinder, lines of E run nearly parallel to the axis, whereas outside, they leave the surface almost radially with just a small forward tilt. There are alternate bands of positive and negative surface charge moving as a wave in the axial direction. The lines of E emerge from a positive band and return to a negative band with a few terminating at infinity in the radial direction.

(5) *Goubau Wave.* Whereas finite conductivity is necessary for the existence of the Sommerfeld wave, the Goubau wave relies upon a surface modification. A major change is that the Goubau wave can be much more concentrated in the vicinity of the conductor. The basic theory is much like that which governs the Sommerfeld wave, although it's more complicated. For example, if the modification is that of a dielectric sleeve, three media are involved. If the modification is due to a variation in the conductor surface, such as corrugations or braid, then there are only two media, but the boundary conditions are more difficult to impose. In either case, a reduced phase velocity (relative to the surrounding medium) occurs, and this produces a surface wave as in the Sommerfeld case. Recall, though, that the Sommerfeld velocity reduction was due to finite conductivity rather than a surface modification. A reduced phase velocity is not a requirement for the existence of a surface wave.

Consider a coaxial cable with a corrugated outer conductor. The troughs in the corrugations may be considered as a series of short-circuited transmission lines perpendicular to the coax; these corrugations can support a traveling wave.[38] This produces an axial (longitudinal) electric field and therefore a forward tilt in the vector E, hence a bound wave. Note also, that the troughs act as reactive circuit elements that store energy from the primary wave.

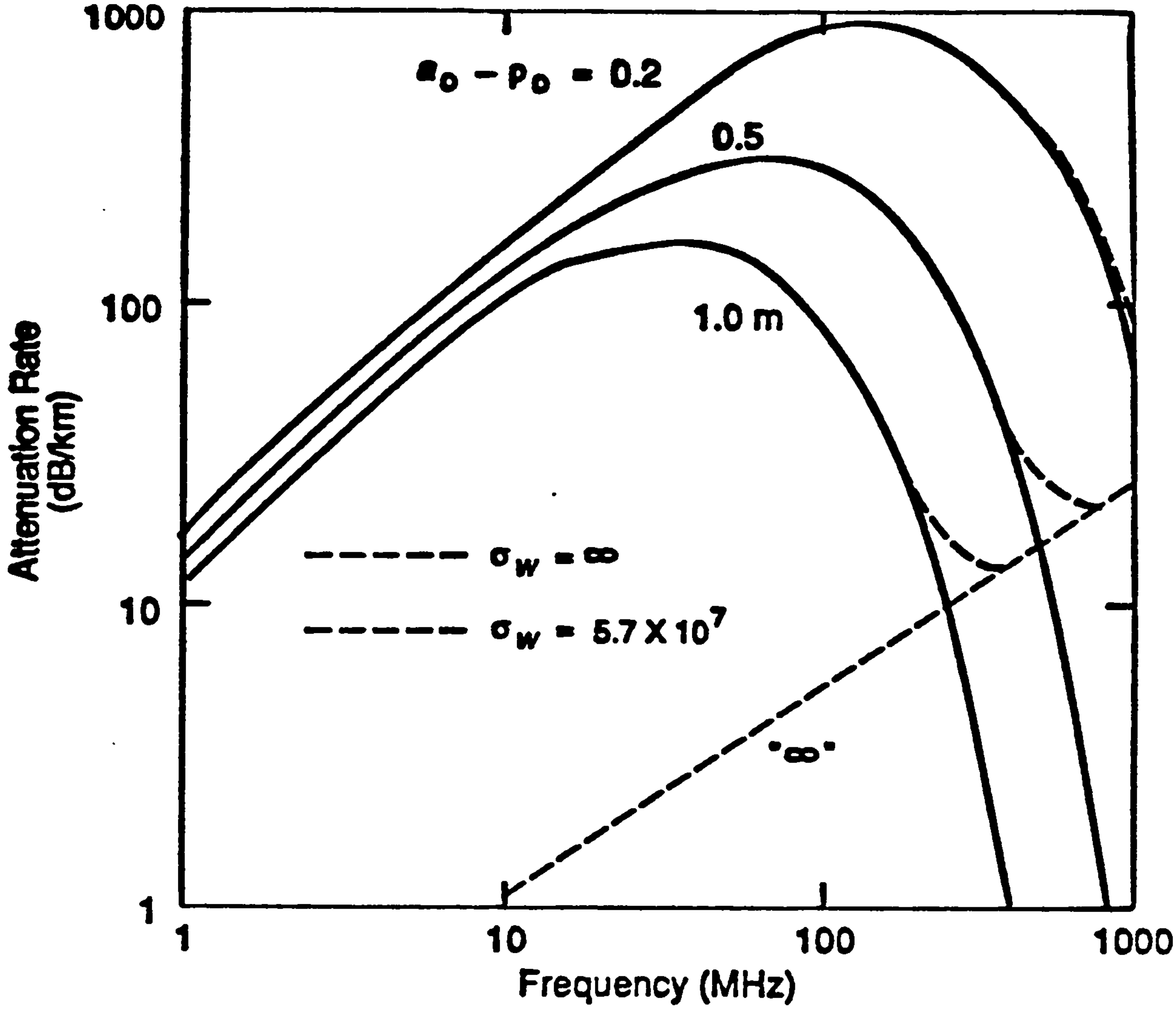
A dielectric coating on the conductor presents a problem of three media and two surfaces. The solution is straightforward, as are the boundary conditions. The result is a propagation of energy in both the coating and the surrounding medium, although most of the power exists in the latter. Radial attenuation in the coating is exponential with an attenuation coefficient given by $(2\pi/\lambda)\sqrt{\kappa-1}$, where κ is the coating dielectric constant, and λ is the free space wavelength.

Coax Modes. In the absence of conductors parallel to the travel walls, the propagation mode was treated previously under the heading "Waveguide Modes." In this situation, a cutoff frequency obviously occurs, below which the wave is severely attenuated. In practice, numerous coaxial cables, power lines, telephone lines, pipes, and usually railroad track run parallel to the tunnels. Thus, while the waveguide modes may still exist, the presence of axial conductors allows the propagation of a TEM with no cutoff frequency. This wave is quite complicated due to the presence of so many parallel conductors; nevertheless, it can be treated in an idealized case.

For example, consider a signal wire (cable, pipe, etc.) suspended in and parallel to the tunnel. At low frequencies, the system resembles a large coaxial cable. As the frequency increases, the wire begins to act like a Goubau line, supporting a surface wave (treated in the last section). As another example, consider a two-wire transmission line (perhaps like a railroad track). Here there are two modes, the monofilar and the bifilar.[39] The monofilar mode corresponds to a guided wave between the transmission line and the tunnel walls, whereas the bifilar mode is much like a balanced, antiphased current in a typical two-wire line.

In what follows, it will be assumed that a conductor (again, wire, pipe, cable, phone line, track, etc.) is placed in an arbitrary position in the tunnel and runs parallel to the tunnel walls. The objective is to qualitatively treat attenuation, effect of wire properties (size, conductivity, coating), placement, and phase velocity.

(1) *Attenuation.* The attenuation of the coaxial mode is really quite complex because it depends upon wire location and frequency in addition to both wire and tunnel wall electrical properties. Refer to the figure that shows attenuation in dB per unit length as a function of frequency.[40,41]
At low frequencies (perhaps less than 10 MHz), the results are similar to that of a bare wire with no insulation. The attenuation increases approximately at a rate proportional to the frequency and goes through a maximum, corresponding to maximum tunnel wall absorption. As frequency increases,



Attenuation rate of mode that behaves as axial surface wave at high frequencies for dielectric-coated conductor located in circular tunnel. Case indicated by "∞" corresponds to having conductor located in free space. For example shown, $a = 1$mm, $c = 5$mm, $a_0 = 2$m, $\varepsilon_s/\varepsilon_0 = 2.56$, $\mu_s = \mu_w = \mu_0 = 4 \times 10^{-7}$, $\sigma_e = 10^{-3} = 1$ mmho/m, $\varepsilon_e/\varepsilon_0 = 5$, and $\varepsilon_0 = 8.85 \times 10^{-12}$. $a_0 - \rho_0$ is the distance of the conductor from the tunnel wall.

the attenuation begins to decrease because the energy density is becoming more concentrated around the wire as in a surface wave. The attenuation then goes through a minimum and begins to increase. The enhancement is caused by the finite conductivity of the wire as it affects the surface wave.

The placement of the conductor in the tunnel has an important effect on attenuation. Minimum attenuation occurs when the wire is located at the geometrical center, and it increases as the wire approaches the wall, as the figure shows. This is important in tunnel shots because all of the conductors are strung near a wall. It also turns out that the TEM mode is most affected by conductor placement compared with higher order modes.[42]

(2) *Dependence Upon Wire Conductivity, Dielectric Coating, and Tunnel Conductivity.* As one would expect, increasing the conductor conductivity decreases the attenuation; in fact, the TEM mode becomes virtually cut off as the conductivity is decreased.[43]

In general, the main effect of a dielectric coating is to lower the attenuation at high frequencies. At low frequencies the dielectric thickness has a negligible effect, whereas at high frequencies, lower attenuation is associated with thicker dielectric coatings.[44]

The influence of the tunnel wall conductivity is as one might expect, namely, lower conductivities are associated with higher attenuation. Yet recall that as frequency increases, a surface wave becomes more concentrated in the wire vicinity, so that the tunnel wall conductivity becomes less influential.

(3) *Effect of Wire Placement on Field Distribution.* It's not difficult to estimate the electric field configuration for an arbitrary placement of a single conductor in a tunnel, especially if the tunnel walls have high conductivity, in which case the E field must be perpendicular at the walls. For example, a wire strung in the center of a circular tunnel would cause a planar projection of an electric field configuration in the radial direction like the spokes of a wheel. On the other hand, a conductor is normally strung close to a wall, and this produces a field distortion.[45] Furthermore, any return current in the walls is concentrated in that portion of the tunnel adjacent to the wire, which in turn, increases attenuation.

The field distortion has an effect upon potential EMP reception outside the tunnel because the field configuration over the portal area would not be that of the usual homogeneous plane wave often assumed for radiation calculations. In fact, if one were to place a sensor inside the tunnel, it would best be located near the conductor, probably between the conductor and tunnel wall.

(4) *Phase Velocity.* The phase velocity of a wave guided by the conductor has an interesting functional dependence upon distance from a tunnel wall. If the wire is placed at the tunnel's geometrical center, the phase velocity is less than the speed of light in vacuum (c). As the conductor is moved towards a wall, the phase velocity increases and becomes greater than c. Note that this doesn't violate relativity because the energy propagation travels at the signal velocity (usually the same as group velocity).

(5) *Leaky Cable Communication.* Mention should be made of a technique often used in mines for communications, sometimes called the leaky feeder technique.[46,47] A small amount of radiation is emitted along the cable length due to, perhaps, the use of a sparse braid. Thus, energy (and information) may also be coupled into the cable and possibly detected at the portal.

SUMMARY BY SECTIONS

Explosives

An explosive decomposes rapidly with the evolution of heat and gas. Its capacity for performing work depends upon the available energy and the time rate of change for energy release. Explosions are of three types: physical, chemical, and nuclear. Physical explosions occur without chemical reactions; nuclear explosions involve either or both nuclear fission or fusion. Chemical explosions usually produce simple gases plus heat.

The total amount of released heat is related to the explosion temperature, which is an equivalent temperature depending upon the specific heat and mass of the products and isn't a defined thermodynamic parameter during the explosion when nonequilibrium conditions prevail. Thus, the assumption of a blackbody distribution is incorrect.

Explosion initiation may occur by burning or detonation. Burning is a series of surface chemical reactions whose rate is determined by heat transfer characteristics. Detonation is achieved by means of a shock wave and it's much faster than burning. Often a light pulse is generated at the onset of detonation.

Description and Theory

A time-dependent charge separation in an explosion produces an electromagnetic pulse. The pulse is delayed in time from detonation. The polarization and radial dependence change with sensor location. Often, two distinct pulse groups are detected, probably associated with a direct wave and the interaction of the shock with the earth. An asymmetry must be present in the ionized source so as to produce nonzero, time dependent multipole moments. Aside from bulk sources, any individual accelerated charge will produce a signal.

Time Delay

Experimental results are consistent in detecting time delays between detonation initiation and the appearance of an electromagnetic pulse; the results are inconsistent in the extent of the delay. Typical times are on the order of 200 μs. For the cases where two distinct pulses are detected, the first is delayed by about 300 μs and the second by about 3 ms. The delay may be proportional to the cube root of the charge mass.

Polarization

Very little information is available on pulse polarization. Theoretical reasoning suggests that an explosive mass near the earth should produce a larger vertical electric field compared with horizontal due to the asymmetry caused by the earth's surface.

Spectrum

Quoted frequency ranges vary from 1 Hz to an excess of 100 MHz. Possibly the spectrum shifts to lower frequencies with increasing mass. Theoretically, the spectrum should broaden to higher frequencies as the detonation time is shortened.

Explosive Mass Dependence

Limited evidence suggests that the time delay between detonation and the pulse appearance varies as the cube root of the mass, whereas the electric field magnitude is directly proportional to the mass.

Radial Dependence

The radial dependence of the electric and magnetic fields depends upon the relative magnitudes of three quantities: source dimensions (D), wavelength (λ), and distance from the source to the detector (r). For example, close to the source with $D \ll r \ll \lambda$, the electric field varies as $1/r^3$. Far from the source with $D \ll \lambda \ll r$, E goes as $1/r$.

Intermediate distance produces a $1/r^2$ dominant dependence. This explains why various experimenters often quote different radial dependence functions.

Field Strength

Field strengths quoted in the literature vary so much as to be confusing and misleading. Clearly, $|E|$ depends upon such experimental factors as source to sensor distance, explosive mass, type of charge, method of detonation, polarization, receiving bandwidth, etc. Inside the source, figures as high as 10^5 V/m are suggested.

Propagation Characteristics and Ground Influence

Two important propagation modes exist for detection of EMP from chemical explosions: (1) propagation along the earth's surface, (2) as a direct wave plus possibly the superposition with a ground reflected wave.

The ground wave follows the earth's contour. It's attenuated rather well for frequencies above 3 MHz. The electric field is mainly perpendicular to the earth's surface, but it always has a forward tilt. The phase velocity is less than the speed of light in vacuum, and the energy density drops off with altitude.

In the far field free space, both E and H have a $1/r$ dependence. If the direct wave has a ground reflected wave superimposed upon it, then E and H drop off as $1/r^2$. The field strength varies approximately as the product of both source and receiving antenna height. These characteristics result in a weak EMP signal much beyond the horizon. On the other hand, a temperature inversion enhances over-the-horizon propagation via atmospheric refraction.

Sensors

Four general types of sensors can be used for EMP detection: (1) antennas, (2) current monitor transformers (coils), (3) B-dot probes, and (4) D-dot probes. The B-dot and D-dot detectors measure time rate of change of surface current and surface charge density, respectively. The coils are placed around a conductor and measure the total conduction current threading through the perimeter; they sense magnetic field (not its time derivative).

Possible antennas for EMP detection are: monopole, dipole, Yagi, log periodic, slot, bicone, helix, and Beverage. The main properties of these antennas are described in the paper. These sensors are always involved in time domain, not steady-state frequency domain measurements; hence, the usual textbook treatments are only partially valid.

Propagation Through a Tunnel

A chemical explosion in a tunnel generates an electromagnetic pulse that propagates through the tunnel in both waveguide and transmisssion line modes; the latter are more important. There is no cutoff frequency because of the presence of conductors parallel to the tunnel, so that the progagation takes the form of surface waves guided by the conductors (phone lines, railroad tracks, power cables, etc.) and common mode between the various conductors. Decoupling the explosive mass for seismic effects by placing it in a cavity will enhance the electromagnetic coupling and this should increase the EMP. The phase velocity and attenuation are functions of conductor location and frequency.

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