Measurement Notes

Note 17

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Some Design Considerations for Signal Transmission Lines for Use with Sensors in a Nuclear Radiation Environment

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Abstract

This note considers two design approaches for signal transmission lines used to transport signals from sensors in an intense transient nuclear radiation environment to locations outside that environment. One approach is a metal-dielectric transmission line with grids for signal conductors, an outer electromagnetic shield, small and matched atomic numbers of the materials, and an outer graded atomic number nuclear radiation shield. The second approach is a metal-vacuum transmission line with similar grids and electromagnetic and nuclear radiation shields; it also has additional grids that are biased to collect low energy electrons that would otherwise pass between the signal grids. The various features of both types of cables are discussed and some tradeoffs are indicated where conflicts exist.

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Contents

List of Illustrations

I. Introduction

After a lapse of many years this note resumes the consideration of design techniques for measurements of quantities associated with the nuclear electromagnetic pulse (EMP) in nuclear source regions. Previous notes[1,6,8,9,10,11] have considered the sensor problem for measuring electromagnetic quantities in nuclear source regions. Another important problem concerns the transmission of signals from such sensors (as well as nuclear radiation sensors and sensors for other physical quantities) to recording instruments outside the nuclear source region (unless the recording instruments are sufficiently hardened and placed inside the nuclear source region). The particular aspect of the nuclear source region that we are concerned with in this note is the charge motion induced by nuclear radiation, in particular γ and X rays, in materials that are present.

A common technique for transporting an analog signal from a sensor to a recorder is to use a transmission line or cable. Good quality cables are characterized by a characteristic impedance and a delay which are approximately independent of frequency. Such a signal cable is inherently a simple device in that it is passive and is characterized by electrical parameters which apply on a per-unit-length basis.

When exposed to a nuclear radiation environment, however, certain problems arise. Charged particles (principally electrons) are set in motion by high energy photons (γ rays and X rays) interacting with the materials of the cable. These electrons produce a signal (a noise signal) in the cable; this noise signal mixes with the desired signal from the sensor, thereby introducing error into the measurement.[10,23,24] Furthermore, if the cable uses insulating dielectric the dielectric material is made conducting in a transient sense as the electrons pass through it; this can change the signal transmission characteristics of the cable and thus introduce errors in the measurement.[23,24]

This cable problem applies to all the types of sensors which send analog transient (real time) signals along such cables from a region with intense transient nuclear radiation. As such it is of concern in cases of sensors for electric fields, magnetic fields, current densities, γ rays, X rays, neutrons, and other related quantities of interest to EMP studies. In considering the nuclear radiation effects in designing various types of electromagnetic sensors various design techniques were developed to minimize the adverse effects of the nuclear radiation on the sensor performance. Some of these techniques can be applied to the problem of hardened signal cable design as is discussed in this note. I have recognized these applications for many years now and I wish I could have had time to write this note some years ago.

One obvious technique for reducing the noise signals and conductance changes in the cable is to use shielding to reduce the nuclear radiation reaching the cable. Such a shield would surround the cable and extend from the sensor for a distance sufficient to get the cable outside the intense nuclear radiation environment. This shield need not be very long (say a few meters) provided the cable is passing through a dense medium (such as soil, etc.). In such cases the length of the special hardened cable (inside the shield and connecting into the sensor) need not be very long either. The length of hardened cable plus external shield is not like an ordinary cable; it is a very special item like the sensor to which it is attached. The basic requirement on this length of hardened cable (plus shield) is that it work in the sense of faithfully transmitting the sensor signal; flexibility etc. is secondary. Note that while shielding has some benefits there are disadvantages associated with the change (attenuation) of the nuclear radiation environment which is also the source of the nuclear EMP to be measured.

Two basic techniques are considered in this note for making the cable itself less sensitive to noise signals generated by photons transporting electrons through the cable. The first is to make the cable conductors have a smaller photon cross section by making them out of grids of wires such as are used in the electric field sensors.[6] The second is to use materials of small and closely matched atomic number (Z) to reduce the number of electrons per unit photon and to minimize the difference of the electron generation between materials.

There are two types of hardened cable designs. The first and perhaps more practical from a construction and operation viewpoint uses a dielectric material for an insulator. The second uses a vacuum dielectric with additional biased grids to collect the low energy electrons emitted from the principal grids serving as the cable conductors. Note that these techniques apply to both coaxial and twinaxial types of cable designs. The twinaxial type of cable design has an additional hardening feature (beyond the coax) associated with its symmetrical differential design.

II. Metal-Dielectric Type of Transmission Line

Consider first the design principles and general description of the metal-dielectric type of transmission line. Figure 1 shows the general layout of the cross section of such a transmission line for two cases commonly employed for transmitting single analog signals. These two cases are coax and twinax and can be considered to have any of the standard impedances or impedance combinations appropriate to such signal transmission lines. Each of the configurations in figure 1 consists of one or more grid signal conductors in the "center," a "grounded" grid signal outer boundary conductor around these, and a solid metal electromagnetic shield around all these. A solid dielectric fills the volume inside the electromagnetic shield except for the small volume of the grid conductors. Outside the electromagnetic shield there may be an additional nuclear radiation shield.

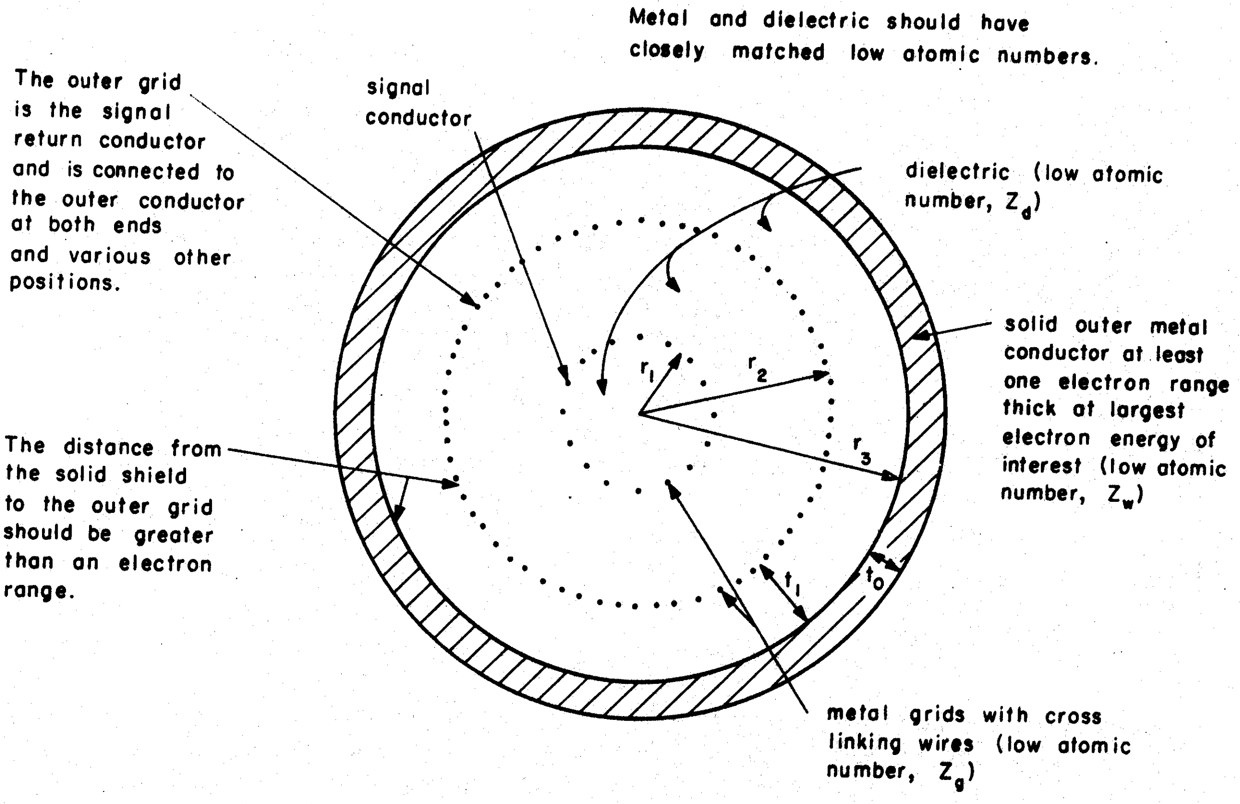
A. Grid conductor currents from photons

The first important feature of the design is the grid conductors. This important design feature is similar to that employed in electric field sensors for use in nuclear source regions for some years now.[6,8,9] In particular a grid has the important advantage of behaving approximately as a highly conducting sheet for frequencies with wavelengths large compared to the wire spacing and distances between inter wire connections on the grid. For photons (γ and X rays) and electrons, however, the grid is mostly transparent in that such photons and electrons can pass through the grid with a low probability of striking a grid wire. Likewise, few electrons are emitted from the grid in comparison to those emitted by a metal sheet of similar thickness. This situation is illustrated in figure 2.

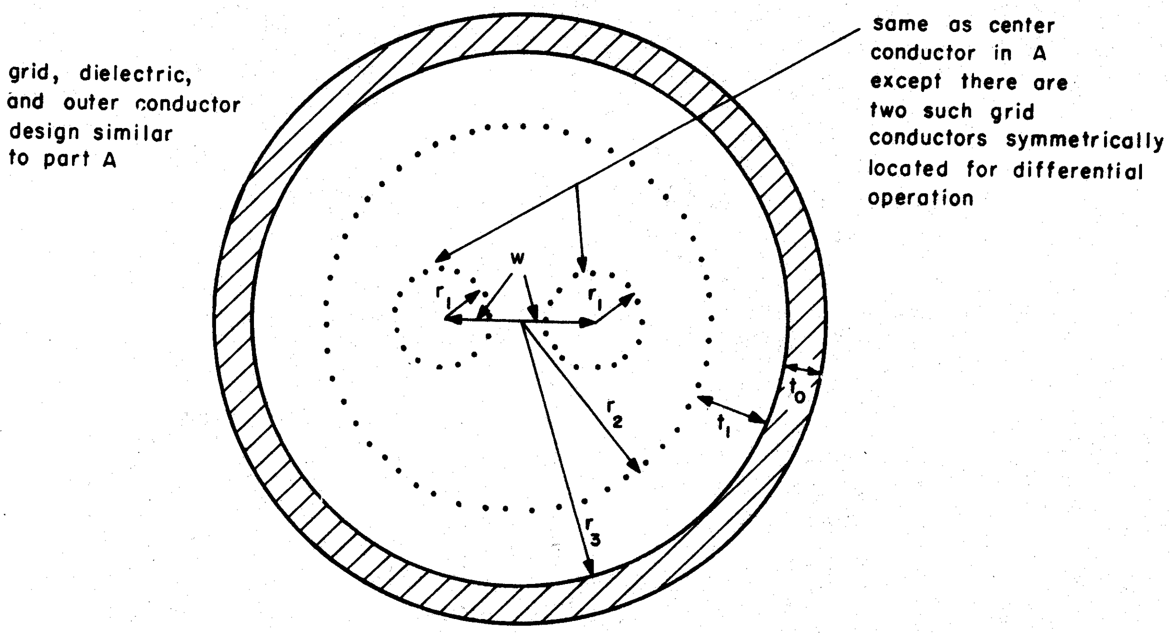
For such a grid one can define a geometric reduction factor for the grid as

$$e_g = \frac{2a}{d} \tag{2.1}$$

This factor is merely the fractional area (for normal incidence) presented by the grid to the incident photons. Note that e_g can be calculated for various grid designs such as for meshes with cross connecting wires or various angular directions of wires (locally approximately in a common plane). This geometric factor is particularly appropriate for the case that the electron range, r_e, in the wire grid is small compared to the wire radius, a.



A. Coaxial



B. Twinaxial

Figure 1. Metal-Dielectric Type of Transmission Line

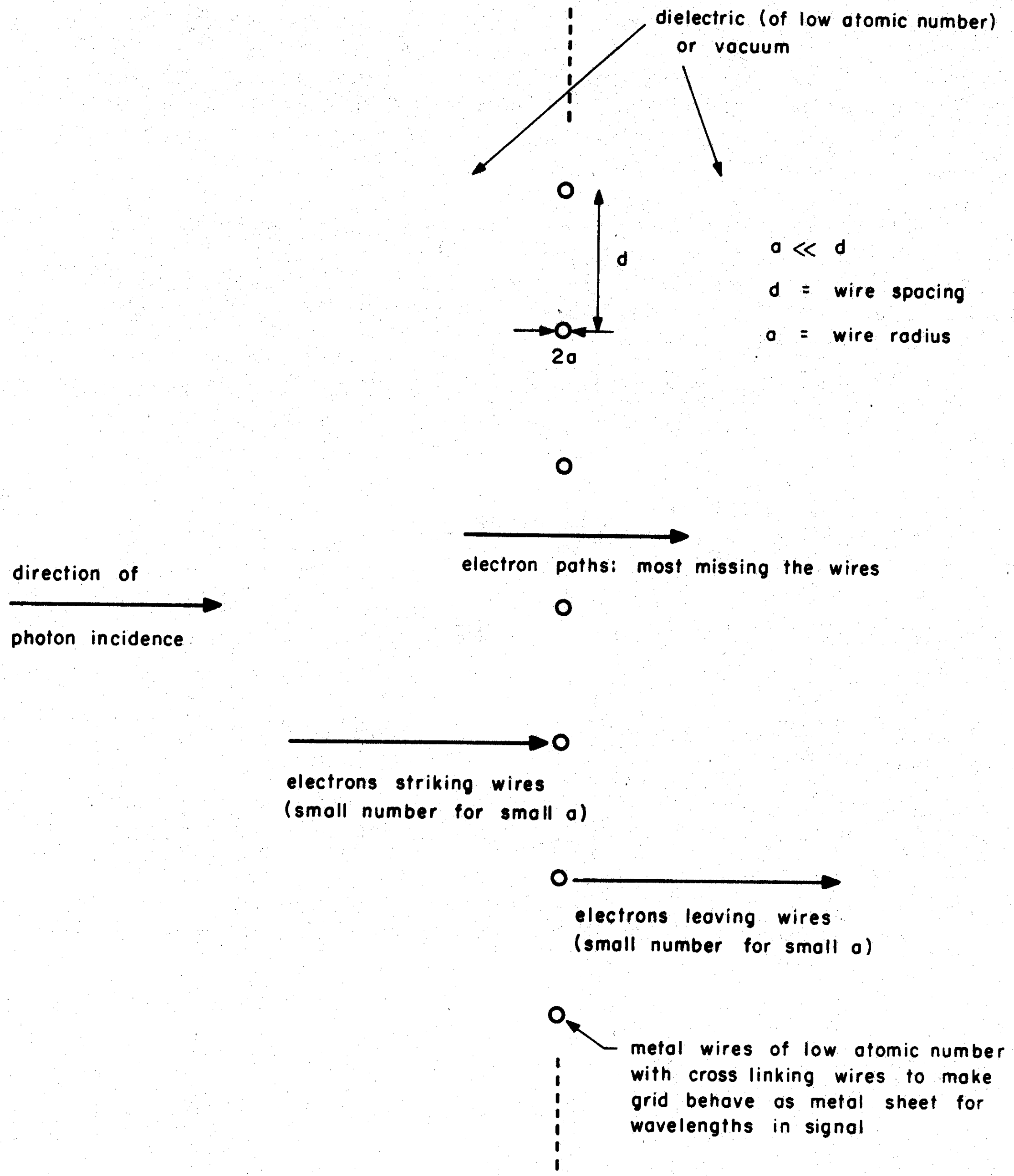


Figure 2. Effect of Grid in Reducing Photon and Electron Interaction with Signal and Return Conductors

The electron range is dependent on the electron energy and thus on the energy of any photons producing such electrons. For small wire radius, a, the photon energy for $r_e << a$ would correspond to low energy X rays. If the atomic number, Z_g, of the grid material were the same as that of the dielectric, Z_d, then the electron transport in and near the wires would leave comparatively little net charge transport into or out of the wires; this is rather desirable from the point of view of minimizing noise signals. This does point out that the average Z_g and Z_d should be made as close together as practical.

If one estimates the current density of electrons, J_c, driven through the dielectric by the radiation then the fraction of this current density into the grid is roughly bounded in magnitude by e_g. It is somewhat less than this if Z_g is near Z_d.

Another consideration in estimating the current into (or out of) such a grid is based on the mass of the grid. If $r_{eg} >> a$ where

r_{e_g} = electron range in grid material

r_{e_d} = electron range in dielectric

r_{p_g} = photon mean free path (single scatter) in grid material (2.2)

r_{p_d} = photon mean free path (single scatter) in dielectric

then the current density of photon driven (first scatter) electrons in the dielectric is

$$J_d = -en_p \frac{r_{e_d}}{r_{p_d}} \tag{2.3}$$

where the electron range is typically (but not always) taken as a mean forward range and where n_p is the number of photons per unit area and time and e is the magnitude of the electron charge. The current density associated with a grid wire for $r_{eg} > t$ is (thin grid wire)

$$J_g = -en_p \frac{t}{r_{p_g}} \tag{2.4}$$

where t is the local wire thickness. The current per unit length of grid wire is then

$$I' = -en_p \frac{A}{r_{p_g}} \tag{2.5}$$

where for circular wire

$$A = \pi a^2 \tag{2.6}$$

where A is the cross section area. For parallel grid wires the fractional current associated with the grid wires is just

$$e_m = \frac{I'}{J_d d} = \frac{1}{d} \frac{A}{r_{p_g}} \frac{r_{p_d}}{r_{e_d}} = \frac{A}{dr_{e_g}} \frac{r_{e_g}}{r_{p_g}} \frac{r_{p_d}}{r_{e_d}} \tag{2.7}$$

For sufficiently high photon energies and sufficiently low atomic numbers the ratio of electron range to photon mean free path is approximately material independent giving

$$e_m \simeq \frac{A}{dr_{e_g}} = \pi \frac{a}{d} \frac{a}{r_{e_g}} \tag{2.8}$$

This approximation is appropriate for the higher photon energies. Comparing equation 2.8 to equation 2.1 note that for thin grids (compared to r_{eg}) there is an extra reduction factor of $(\pi/2)(a/r_{eg})$ over the case of thick grid wires. This case of thin grid wires then has a mass or volume reduction factor, e_m (instead of an area reduction factor, e_g, for thick grid wires).

Some typical ratios of electron range to photon mean free path in aluminum are listed in the following table.[14,18,19,22]

ψ_p (photon energy)	r_e/r_p (electron fraction)	
30 keV (photoelectric)	5×10^{-4}	with a dependence of about ψ_p^{-1} far from absorption edges
few MeV (compton region)	7×10^{-3}	
fission γ-ray spectrum	3×10^{-3}	

Table 2.1 Typical electron fractions (effective r_e/r_p for aluminum)

Some typical electron ranges (extrapolated range or maximum range for monoenergetic electrons) are listed in the following table.[21]

ψ_e (electron energy)	r_e	ρr_e (ρ = density)
10 keV	$.7 \times 10^{-6}$ m	2×10^{-3} kg/m^2
100 keV	$.5 \times 10^{-4}$ m	.13 kg/m^2
1 MeV	1.5×10^{-3} m	4 kg/m^2
10 MeV	1.9×10^{-2} m	50 kg/m^2

Table 2.2 Typical electron ranges (extrapolated) for aluminum

For comparison we have some typical photon mean free paths based on mass absorption coefficients in aluminum in the following table.[21]

ψ_p (photon energy)	r_p (photon mean free path)	M_a (= $1/(\rho r_p)$) (M_a = mass attenuation coefficient)
10 keV	1.5×10^{-4} m	2.4 m^2/kg
100 keV	.026 m	.016 m^2/kg
1 MeV	.07 m	.006 m^2/kg
10 MeV	.18 m	.0023 m^2/kg

Table 2.3 Typical photon mean free paths from mass attenuation coefficients for aluminum

Considering the electron ranges in table 2.2 note that even thin grid wires will be thicker than an electron range at the smaller electron energies, so the approximation for fractional current associated with a grid (equation 2.1 or 2.8) will depend on the electron (and thus photon) energy. On the other hand the grid will be thin compared to most photon mean free paths (as in table 2.3).

The present calculations have been made for aluminum because it is commonly available and has a low atomic number ($Z_{Al} = 13$). Low atomic numbers are desirable for reducing photon interaction effects, particularly at low photon energies where the photoelectric cross section varies as Z^n where n is 4 roughly.[21] For γ-ray interaction the variation of the cross section with Z is not so important but for X-rays it can be quite a large effect. In addition a reduction in atomic number generally implies a decrease in mass density and a proportional increase in the electron range and photon mean free path in the material of interest. This lowers e_m in equation 2.8.

For convenience we can note that one photon/m^2 is equivalent to various other units in the following table.

ψ_p (photon energy)	Energy flux per unit area	$M_{p_{Al}}$ (mass absorption coefficient in Al)	Dose
10 keV	1.6×10^{-15} J/m^2	2.4 m^2/kg	3.84×10^{-15} J/kg (3.87×10^{-13} rad)
100 keV	1.6×10^{-14} J/m^2	.0038 m^2/kg	6.1×10^{-11} J/kg (6.1×10^{-9} rad)
1 MeV	1.6×10^{-13} J/m^2	.0026 m^2/kg	4.2×10^{-10} J/kg (4.2×10^{-8} rad)
10 MeV	1.6×10^{-12} J/m^2	.0018 m^2/kg	2.9×10^{-9} J/kg (2.9×10^{-7} rad)

Table 2.4 Energy flux per unit area and dose in aluminum equivalent to one photon per unit area

While the present calculations have assumed a planar grid geometry as illustrated in figure 2 they can be applied for non planar geometries as well. If d is small compared to the radius of curvature of the grid the formulas will still approximately apply. Even if d is not small compared to the radius of curvature of the grid the same practical conclusions result: large d and small a lead to small numbers of electrons transported into or out of the grid conductors.

B. Equivalent dimensions of signal conductor grids

As discussed in other notes[7,12,13] the replacement of conducting sheets by grids can be thought of as a shift of the grid overall dimensions (such as r_1, r_2 in figure 1). The coaxial geometry in figure 1A has r_1 and r_2 replaced by equivalent dimensions with

$$\begin{aligned} r_{1_{eq}} &< r_1 \\ r_{2_{eq}} &> r_2 \end{aligned} \qquad (2.9)$$

The equations and graphs in references 12 and 13 can be used to estimate $r_{1_{eq}}$ and $r_{2_{eq}}$. Roughly speaking the equivalent dimensions differ from the geometrical dimensions by a distance of the general order of d (the wire spacing). Note that the previously developed formulas referenced here neglect the presence of cross linking wires; if the spacing of the cross linking wires is not large compared to d then their effects (at least on the capacitance per unit length) will need to be considered.

The presence of the solid outer metal conductor affects $r_{2_{eq}}$, reducing it somewhat. Note that the solid outer metal conductor is held at the same potential as the outer signal grid for a calculation of $r_{2_{eq}}$. Practically this requires electrical connections between the outer signal grid and the solid outer metal conductor to be spaced at distances small compared to a radian wavelength (in the dielectric) at the highest frequencies of interest. One could calculate the effect of the outer solid metal conductor on $r_{2_{eq}}$ but such is beyond the scope of this note.

The twinaxial geometry in figure 1B is somewhat more complex. A previous note[5] calculates the impedances for a symmetrical twinax with inner and outer conductors as circular cylinders. r_1, r_2, and perhaps w (the mean half spacing) need to be replaced by equivalent dimensions. Estimates of $r_{1_{eq}}$ and $r_{2_{eq}}$ can be made using previously referenced results. Note that for the twinax the presence of cross linking wires also affects the capacitances per unit length.

Note that the grid conductors might be woven at some angle to obtain an average spacing, d, and cross linking automatically. This would of course complicate the calculations of the inductance and capacitance per unit length somewhat but may be desirable for construction or other reasons.

Another effect on the cable impedance is the grid resistance. This should be kept small so that the total resistance over the length of each signal conducting grid (in the special cable length used) will be negligible compared to the desired cable impedance. This may limit how few and how fine are the grid wires that may be used.

C. Metal-dielectric effects

Since this design involves both metal and dielectric then one should be concerned about their relative properties for transporting photon driven electrons. In particular since electrons are driven from the dielectric into the metal and conversely then one would like to have these two currents cancel as well as possible. This design consideration implies that the atomic numbers of the grid (Z_g), outer conducting wall (Z_w), and dielectric (Z_d) all be as near to the same as possible. In order to match the metal and dielectric atomic numbers while keeping the atomic numbers small one might consider the elements in the following table.

Z (atomic number)	Element	
3	Li (lithium)	conductor constituents (metals)
4	Be (beryllium)	
5	B (boron)	
11	Na (sodium)	
12	Mg (magnesium)	
13	Al (aluminum)	
1	H (hydrogen)	dielectric constituents
6	C (carbon)	
7	N (nitrogen)	
8	O (oxygen)	
9	F (fluorine)	
14	Si (silicon)	
15	P (phosphorus)	
16	S (sulphur)	
17	Cl (chlorine)	

Table 2.5 Low atomic number materials for conductors and dielectrics

For use with aluminum conductors a dielectric consisting of carbon, fluorine, and perhaps chlorine might be useful. However, there are perhaps many interesting conductor-dielectric combinations. In matching conductors with dielectrics one could use some average (weighted) atomic numbers for each.

The atomic number matching will not be perfect. The difference in atomic numbers will cause a net current to flow into or out of the various conductor and dielectric regions. Fortunately the grid conductors are made small so that the change in the electron transport for $r_{eg} >> a$ is also small, the wire cross section accounting for only a small number of electrons. However, within one electron range of the solid outer metal conductor there can be a current unbalance in the dielectric associated with the atomic number difference between the two materials. One way to avoid this is as shown in figure 1.

First the outer grid signal return conductor is spaced away from the outer solid conductor by a few electron ranges in the dielectric. This implies that one has an electron range for an electron energy above which the differential electron transport is negligible. The outer signal grid then shields the signal volume (between the grids) from electrical signals associated with the differential transport. This shielding is not perfect but improves with larger spacing of the grid from the solid outer conductor and smaller wire spacing (d) in the grid. Some compromise may then be needed here.

Second the outer conducting shield should be at least one electron range thick ($t_o > r_{e_w}$) at the largest electron energies of interest. This allows the equilibrium electron number and spectrum emitted into the dielectric as well as the backscatter properties of the outer shield to be established.

Suppose that some of the dielectric near the outer conducting shield could be made somewhat conducting with negligible change in the average atomic number. This could short out some of the signals due to the electron transport associated with the differing atomic numbers between the dielectric and the outer conducting shield. This conducting region should not penetrate through the outer conducting grid.

D. Electromagnetic shielding

An additional function of the outer conducting shield is to serve as an effective electromagnetic shield which keeps out external signals. In an EMP environment there are large currents induced on cables. Such currents can be made to flow near the outside surface (within a skin depth at high frequencies) provided sufficient thickness of a high conductivity material is used in the outer conducting shield and the shield topology is maintained continuous around the cable.

Note that while the outer conducting grid is used for signal transport it is not a very effective shield. Thus two outer conductors are used, one for signal transport and one for shielding against external signals.

E. Additional noise cancellation for differential cables

For the case of a twinax cable as in figure 1B there is an additional effect in cancelling noise signals from electron transport into and out of the grids. Since the two center conducting grids are assumed identical then one would expect nearly the same signals with the same sign to be generated in the two inner conducting grids. The two inner conducting grids also have the same coupling to the surrounding dielectric and outer grid (not signal return grid in the case of a twinax). By the nature of a differential signal (two equal and opposite signals) on the center conductors the noise signal will not appear as a differential signal, but rather as a common mode signal.

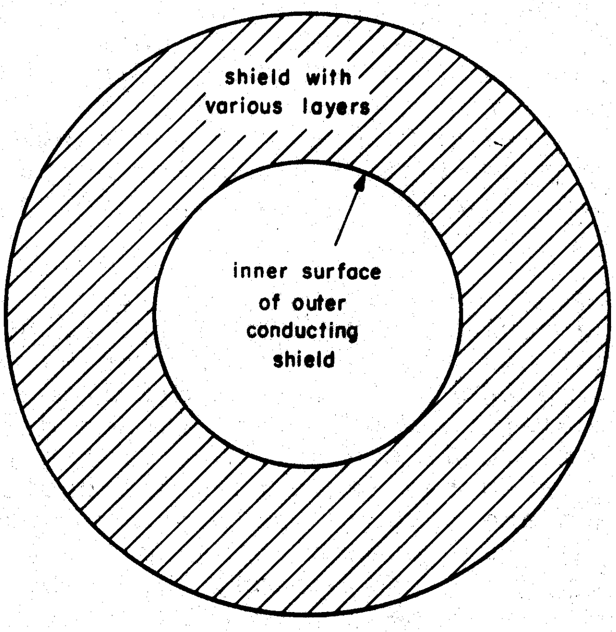
In order to improve the nuclear radiation noise rejection of such a twinax the cable can be optimally oriented with respect to the incident nuclear radiation. One way to accomplish this is to have the incident photons parallel to a plane which is in turn perpendicular to a plane determined by the center lines of the two grid signal conductors. If the photons are incident perpendicular to the cable then the cable would be rotated such that the plane through the center lines of the two grid signal conductors was perpendicular to the photon incidence direction. Of course the photons should be incident uniformly in number per unit time and spectrum over the cable cross section.

An alternate approach is to twist the cable center conductors in a helical fashion around each other so as to make the two conductors have the same interaction with the incident photons when averaged over one period of the twist. The twist period should be small compared to distances over which the photon number (per unit time) and spectrum change significantly.

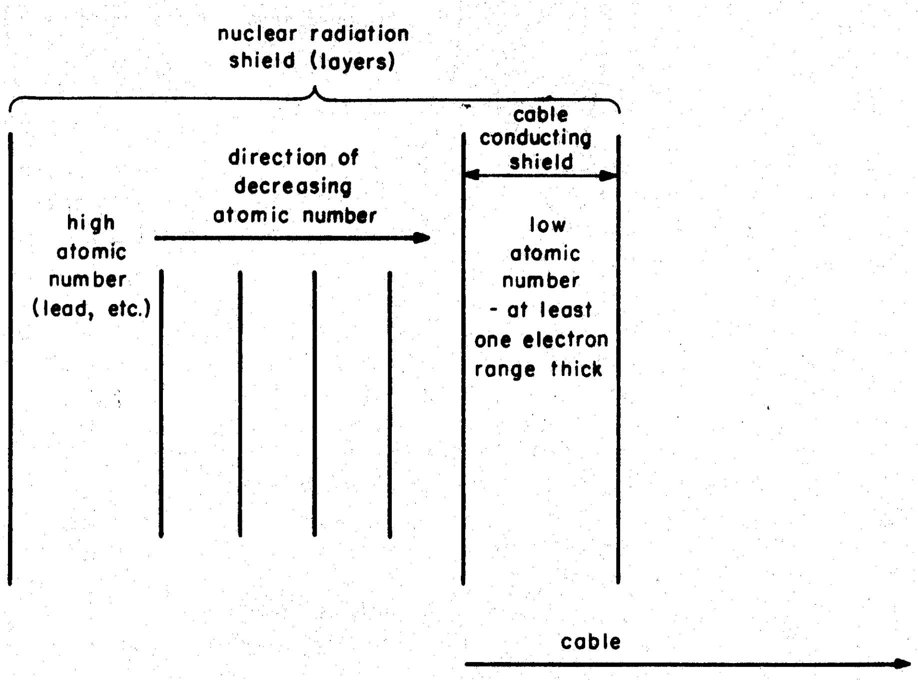
F. Nuclear radiation shielding

The outer conducting shield can serve as part of a nuclear radiation shield. Such a shield would be designed primarily for photon shielding but some attention could be paid to avoiding unwanted neutron effects.

As illustrated in figure 3 such a shield would have large atomic number (Z) materials on the outside layers of a coaxial configuration for maximum attenuation for a given layer thickness. As one went inside toward the signal cable the atomic number would decrease to minimize pair production (electron-positron) near the cable at high energies and to make the K edges, L edges, etc. overlap one another for the different materials at low energies to give a smooth attenuation curve as a function of photon energy. The innermost layer of the photon shield is the outer conducting shield which, as discussed previously, has a low atomic number to match the cable conducting grids and dielectric.



A. Cross section of nuclear radiation shield surrounding cable



B. Layered shield

Figure 3. Nuclear Radiation Shielding Outside of Cable

The thickness of this shield depends on the desired photon attenuation. For X rays such a shield can be quite effective; for γ rays it may need to be somewhat massive. One should note that the shielding thickness can be increased somewhat along the path of the incident (unscattered) photons which would intercept the cable, excluding the outer conducting shield. Another consideration here, however, is that the radiation shield attenuates the photons that would be incident on a portion of the medium around the cable that would have been illuminated were the measurement equipment (including cable) not present. For EMP source regions this distorts the EMP generation. Thus a premium is put on keeping such shielding small in volume.

G. Dielectric conductivity effects

The presence of the nuclear radiation affects the electrical characteristics in another way in that it makes the dielectric somewhat conducting by ionizing it in a transient sense. This gives a transient conductance per unit length to the signal transmission line.[23,24]

The dielectric conductivity is dependent on the local nuclear radiation (dose rate time history) and the characteristics of the dielectric. As such it is not significantly influenced by the grids used for signal transport and return. The conductivity is, however, significantly affected (reduced) by the presence of nuclear radiation shielding around the transmission line.

The question of the optimum dielectric selection for use in such a transmission line is a rather complex question which is beyond the scope of the present note. However, there are a few general considerations one can mention. First, for a given photon environment (particularly for the lower photon energies) a low atomic number (and an associated low mass density) are advantages in reducing the dose rate for a given photon environment. A reduced dose rate implies less ionization in the dielectric. Further dose rate reduction in the dielectric is achieved by reduction of the radiation incident on the dielectric through the use of nuclear radiation shielding around the transmission line and/or routing the transmission line from the sensor out of the nuclear radiation environment by a short path. Note that orienting the transmission line so as to minimize the length exposed to nuclear radiation may conflict with a different orientation which minimizes the distortion of the surrounding EMP environment by the presence of the transmission line.

If the transmission-line diameter is small compared to the photon mean free path, then the dielectric conductivity and associated conductance per unit length (for a fixed dielectric and cable impedance) will be approximately independent of the cable diameter. For larger transmission-line diameters the dielectric thickness will provide some attenuation of the radiation. However optimally designed nuclear radiation shielding around the transmission line will provide more radiation reduction per unit thickness than will added transmission-line diameter.

The conductivity distribution will not be exactly uniform in the dielectric. Thus for a twinaxial design as in figure 1B it would be good to have the cable optimally oriented with respect to the incident radiation so that the conductance per unit length is the same for the two signal conducting grids with respect to the outer grid. This will minimize conversion of signal and noise between common and differential modes. Alternately the two signal conducting grids can be twisted around each other in a helical fashion to try to maintain equal conductances for the two signal conducting grids (with respect to the outer conducting grid) when averaged over a period of the helical twist.

A possible problem of concern is the behavior of the dielectric near where it interfaces with the metal. Charge transport under influence of various electric fields and radiation can be somewhat complicated through such interfaces. One advantage of the designs in figure 1 is that the surface area of such interfaces with the signal grids is reduced in a manner proportional to the geometric reduction factor e_g in equation 2.1. Spurious signals generated in the dielectric near such interfaces can then be somewhat reduced. In addition the dielectric penetrates through the grid allowing charge transport through the grid while remaining in the dielectric and not having to pass through a metal-dielectric interface. Of course there is a significant interface at the outer conducting shield but noise in this region is somewhat shielded from the signal region by the outer conducting grid.

A low impedance source driving the cable is desirable since it appears in parallel with the radiation-induced cable conductance (and the cable impedance) at the lower frequencies. This applies for times large compared to transit times from the signal source to the farthest significantly conducting cable dielectric. There is also a cable inductance term between the signal source and the conducting dielectric which can slow the equilibration of the signal transported away from the source region to that put out by the source; this is basically an inductive-resistive limitation of a low-pass-filter type. The conductance induced by the radiation and the associated cable inductance are both reduced by minimizing the cable length exposed to the radiation where the signal source (sensor) is located in the radiation environment.

Inductive sensors with small inductances (such as B-dot and I-dot sensors with inductances of the order of nanohenries) are quite appropriately used as low impedance signal sources.

As discussed in a previous note[10] the use of such signal sources helps to short out the noise signals generated in the cable; the remaining noise is proportional to the square of the length of exposed cable. Our present considerations indicate a similar effect as a time limitation associated with the induced cable conductance.

In general the dielectric conductivity problem is a difficult one, but as discussed here some alleviation of this problem is possible. Clearly one would like to choose dielectrics with minimum conductivity under radiation. While some information is known about the conductivity of various dielectrics one should be able to minimize the radiation induced conductivity by developing special dielectrics for this application.

H. Transmission line cross section size

As discussed previously the cable diameter is not too important in minimizing radiation induced conductivity; nuclear radiation shielding is more significant in this case. Nuclear radiation shielding helps reduce radiation induced currents in the grids as well. The cable cross-section size, however, has some effect on the radiation induced current sources.

If the cable cross section size (diameter) is increased then the radiation currents induced in the grids will tend to increase. If the number of grid wires is proportional to the diameter then one might expect the noise to be proportional to the first power of the diameter. Volume effects such as charge deposition associated with radiation attenuation in the dielectric could produce noise proportional to the square of the diameter. Such effects would indicate small diameters as desirable.

A larger cable diameter would give a larger signal voltage handling capability, say proportional (roughly) to the first power of the diameter. A larger signal of course increases the signal-to-noise ratio. One should then consider the signal available from the signal source, and have the cable diameter large enough to handle the signal voltage (in the presence of the radiation).

There are various practical construction problems in building such a cable; these will also have some impact on the cable size. One will then have to trade off various factors in determining the appropriate cable diameter, not too big and not too small. It would be useful to build and test such cables in several diameters.

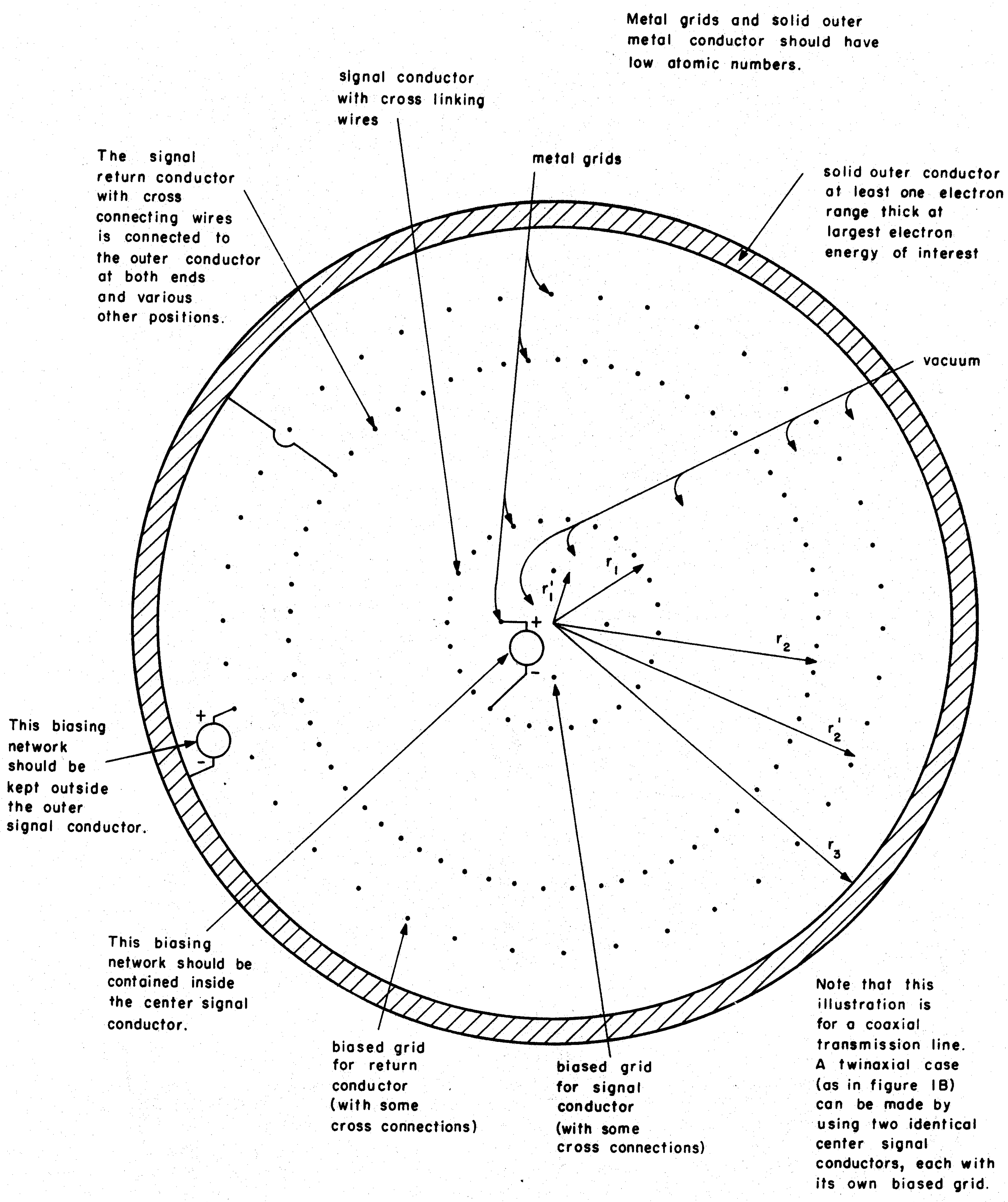
III. Metal-Vacuum Type of Transmission Line

In this section let us consider an alternative design concept for signal transmission lines in a nuclear radiation environment. As illustrated in figure 4 this concept involves a set of grids similar to the design considered in section II. However the dielectric material is replaced by a vacuum and additional electron collecting grids are included. While figure 4 only illustrates the case of a coaxial transmission line, the same design concept is readily extended to twinaxial cables. Just as in the metal-dielectric case in figure 1 where the twinaxial configuration is obtained by replacing the center signal conducting grid by two such grids symmetrically placed, the twinaxial metal-vacuum case has two symmetrically placed signal conducting grids, each with an electron collecting grid inside it. The two sides of a twinaxial system should be maintained geometrically and electrically (i.e. grid bias) the same.

The first design feature to consider is the vacuum dielectric. As discussed in section IIC it is desirable to have nearly the same atomic number materials in (or near) the signal transport region between the appropriate grid conductors. If the various conducting grids and the outer conducting shield are all made of the same (or nearly the same) material then the atomic numbers will be closely matched. Of course removal of the dielectric material will mean that certain design considerations (including some considerations in section II, subsections C, G, and H) are not directly relevant.

Some of the previous design considerations carry over directly. In particular the desirability of using grids for "boundaries" of the signal transport portion of the cable cross section as in section IIA carries over directly to the vacuum type of transmission line. Note, however, that the appropriate noise current density in the vacuum, while approximately the same as in equation 2.3, is emitted from the outer conducting shield in the vacuum-dielectric design. The equivalent grid dimensions as in section IIB also carry over directly, as do the electromagnetic shielding in IID, the differential noise cancellation in IIE, and the nuclear radiation shielding in IIF.

The metal-vacuum cable has some special design considerations of its own. First let us consider a special effect associated with the low energy electrons. There is a significant low energy portion (hundreds of eV) of the spectrum of electrons emitted from the metal surfaces. Such electrons can be collected by various of the conductors depending on the electric field distribution in the vacuum and the associated potentials of the conductors. A SEMIRAD (a type of nuclear radiation sensor) collects such electrons to give a signal proportional to the incident nuclear radiation time history.[3,4]



Metal grids and solid outer metal conductor should have low atomic numbers.

signal conductor with cross linking wires

The signal return conductor with cross connecting wires is connected to the outer conductor at both ends and various other positions.

metal grids

solid outer conductor at least one electron range thick at largest electron energy of interest

vacuum

This biasing network should be kept outside the outer signal conductor.

This biasing network should be contained inside the center signal conductor.

biased grid for return conductor (with some cross connections)

biased grid for signal conductor (with some cross connections)

Note that this illustration is for a coaxial transmission line. A twinaxial case (as in figure 1B) can be made by using two identical center signal conductors, each with its own biased grid.

Figure 4. Metal-Vacuum Type of Transmission Line

The function of the biased grids is to collect such low energy electrons emitted from nearby grids and/or metal shield. In particular it is desirable that the biased grids reduce the number of low energy electrons crossing the space between any signal grids including signal return (or outer signal "boundary" grid in the case of twinax). The biased grids are charged positive with respect to their adjacent signal grids to collect the low energy electrons from such grids. In addition the outermost biased grid collects a significantly larger number of low energy electrons from the outer conducting shield. Each biased grid should have a potential (with respect to its adjacent signal grid) which is large compared to the magnitude of the energy per unit charge of the low energy electrons; this inequality should be maintained during the radiation transient. Note that the outer conducting shield is maintained at the same potential as the outer signal "boundary" grid. The bias potentials should also be large enough compared to the signal magnitude so that the signal potential does not have a significant effect as far as moving low energy electrons across the space between the signal grids.

The biased grids need to be connected to power supplies in order to maintain the bias potentials. Not only must the initial bias be established but it must be maintained for times of interest during the nuclear radiation pulse. A significant design problem is the design of such bias control equipment. One requirement is that no significant transient currents be transported across the space between the inner and outer signal grids (or between any two of the three signal grids in the case of twinax). As illustrated in figure 3 the bias potential sources (or at least circuit elements for the maintenance of the potentials for signal times of interest) should be contained inside the inner signal grid(s) and outside the outer signal return or "boundary" grid.

In the case of the outermost bias grid the positioning of bias circuitry outside the outer signal grid should not be difficult. However, the positioning of the bias grid(s) inside the inner signal grid(s) is a more difficult problem because of the small cross section size of the signal grid(s). The inner signal grid(s) may need to be enlarged somewhere along the length of the cable so as to enclose the appropriate bias equipment; the outer grids and/or shield may have to be enlarged at the same cross section location to preserve the desired cable impedance.

It may be important to keep various parts of the bias equipment outside of the more intense nuclear radiation region. Since in general the most intense nuclear radiation is near the signal source (sensor) and the cable is routed from the sensor to a region with less nuclear radiation, then the most radiation sensitive parts of the bias equipment should be placed at the portion of vacuum-dielectric cable farthest from the sensor.

Note that certain of the components of the bias network may need to be distributed along the cable so as to maintain certain desirable transient characteristics along the entire vacuum dielectric cable.

While the bias grids are somewhat isolated from the signal this isolation is not perfect and the presence of the bias grids can affect the signal propagation in the cable. Some attention should then be given to the coupling of the signal to the bias grids so as to avoid certain problems such as significant resonances. Lossy grid wires can be used and/or various lumped elements can be distributed in the space inside the inner signal grid(s) and outside the outer signal grid.

One of the noise sources for a metal-vacuum type of transmission line is the current-density (and associated charge density) in the vacuum. This is an SGEMP noise such as has been studied in various notes.[15,16,17,18,19,20] For radiation levels such that the current and charge densities are not significantly affected by the fields the resulting fields are proportional to the first power of the diameter and the resulting current and voltage noise sources are proportional to the square of the diameter. Thus small cable diameters are important for small radiation noise but the cable size is limited for practical construction reasons. Note that for small cable diameters this type of noise is proportional to the time derivative of the radiation driven current density. Also the minimum cable diameter will be limited by vacuum breakdown in the presence of the signal from the sensor.

Another possible design feature for a metal-vacuum transmission line would be the use of magnetic fields to inhibit the passage of radiation driven electrons across the space between the signal grids. For example one might impose a magnetic field parallel to the cable axis so as to force electrons from the outer conducting shield back to it. One should note that the presence of large biasing magnetic fields in an EMP source region outside the cable would generally be undesirable if one wishes to measure the EMP. This problem might be avoided if closed flux paths (say outside but near the cable) are provided for the bias magnetic field. Bias magnetic field may be difficult to achieve practically, but it still has some possibilities.

IV. Summary

This note has considered two approaches toward designing signal transmission lines with minimum noise in a nuclear radiation environment. Some of the design features common to both approaches include the use of grids for signal conductors, an outer conducting electromagnetic shield, small and matched atomic numbers between grid and outer electromagnetic shield, at least one electron range thickness for the electromagnetic shield, and an outer nuclear radiation shield with a graded atomic number with high Z on the outside and low Z on the inside.

The metal-dielectric type of transmission line has some special design features including the atomic number approximately matched to that of the grids and outer conducting shield, and dielectric chosen with minimum radiation induced conductivity in mind.

The metal-vacuum type of transmission line has a few special design features as well including biased grids and associated circuitry for collecting low energy electrons.

Both types of signal transmission lines can be made in coax and twinax versions. This gives added symmetry for noise cancellation, particularly if the cable is optimally oriented toward the nuclear radiation or a helical twist is given the two conducting grids.

Detailed studies of the various features of such transmission lines are needed. The tradeoff between the designs may depend on many factors such as the nuclear radiation current density time history,[2] required high frequency performance, and lengths of the cable to be used. Prototypes should be built, tested, and optimized so that they can be available for use in nuclear radiation environments, whether on nuclear tests or with laboratory pulsed photon sources of various spectral characteristics.

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