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# MCCABE: A CODE FOR CALCULATING X-RAY INDUCED CURRENTS IN SHIELDED CABLES TRW Defense & Space Systems Group One Space Park Redondo Beach, California 90278

28 February 1978

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Final Report for Period May 1977-December 1977

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#### 1.0 INTRODUCTION

This report summarizes the theory and operation of the MCCABE (Multi-Conductor-CABLE code) which is an analytical tool for predicting the response of shielded cables or cable bundles in X-ray environments, and is a multi-conductor generalization of the PICS code reported in Ref. 9. The output of the MCCABE code is the per-unit-length equalent circuit parameters for transmission lines, chief among which is the radiation driven current source terms. The underlying assumptions and limitations of the code are discussed in Sect.2, but the main assumptions are that:

- 1) the cables are in vacuum;
- the incident flux is low enough such that radiation induced conductivity and other limiting effects may be ignored;
- 3) there is no significant x-ray spectral content above 300 keV.

The MCCABE formalism presented in Sect. 2 differs from that in Ref. 1 in that the electron transport routines have been completely revised to use the analytic charge deposition profile analysis recently given by Dellin and MacCallum.<sup>4</sup> The advantage of their deposition profile results (besides computing speed) is that electron production from both materials which form an interface (e.g. conductor and dielectric) is automatically taken into account. The MCCABE code can now calculate the response of a cable made from materials with comparable emission efficiencies (e.g. aluminum and Kel-F).

The operation of the code is discussed in Sect. 3 where sample input and output are also presented. One important feature of the code is an executive subprogram which interrogates the user concerning the input to the code (cable dimensions, materials, etc.). This subprogram sets up all the input files for the problem, and the user doesn't have to concern himself about format. The running time for a coax problem is less than 12 sec CPU time on the CDC 6600, with multi-conductor cables taking longer.

The MCCABE code has been used recently in a parameter study<sup>2)</sup> to determine the sensitivity of cable response to various cable and photon source parameters. Before running the MCCABE code we suggest that the user consult Ref. 2 in order to get a rough idea of how his cable will respond.

At this point the MCCABE code has received preliminary experimental verification in X-radiation experiments conducted at the Simulation Physics facilities<sup>7,8</sup> and the Aerospace Dense Plasma Focus facility<sup>7,9</sup>. References 7-9 concerned either coaxial cable response, or common-mode multi-conductor cable response; Reference 1 considered individual wire response of multi-conductor cable response as well. The fluence at both the SPI and DPF machines was on the order of  $10^{-4}$  to  $10^{-3}$  cal/cm<sup>2</sup>. An experimental program for testing cables is presently underway at the SPI facilities, and will be reported later.

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As mentioned above, the code is applicable to the region where radiation induced conductivity and other limiting effects are unimportant. We believe that the cross-over point occurs at a few tenths of a cal/cm<sup>2</sup>, and that beyond this the response is sublinear. This point is discussed in more detail in Ref. 3. The implication is that MCCABE can still provide worst-case estimates of cable response even at high fluences.

#### 2.0 THEORY OF THE MCCABE CODE

The problem of determining the response of shielded cables to x-rays can be considered in three steps:

- Step 1: Calculation of the photon transport, electron production and transport for the geometry and materials of the cable to determine the profile of deposited charge in cable dielectrics;
- Step 2: Calculation of the radiation driven source terms (Norton equivalent drivers) to be used in the transmission line equations.

Step 3: Solution of the transmission line equations to obtain load response. The MCCABE code carries out the first two steps, again assuming that no limiting occurs and that the radiation transport is independent of any voltages developed along the transmission line. With these assumptions the Norton driver can be inserted into transmission line equations in a separate step. On the other hand, if limiting effects are important, then steps 2 and 3 are coupled and must be solved simultaneously.

In the subsections below we discuss the following topics:

- o transmission line equations and equivalent circuit modeling (Sect. 2.1)
- o cable geometry and photon attenutation (Sect. 2.2)
- o electron deposition in cables (Sect. 2.3)
- o the solution of Laplace's equation in two dimensions (Sect. 2.4)

#### 2.1 TRANSMISSION LINE EQUATIONS AND EQUIVALENT CIRCUIT MODEL

We derive the canonical transmission line equations which include the desired X-ray induced source terms. The key assumption of transmission line theory is that only the TEM mode of propagation is important, and this implies that the electromagnetic fields are normal to the axis of propagation. An immediate consequence of this is that the electric field is derivable from a scalar potential.

#### Differential Voltage Transmission Line Equation:

Consider N wires inside a shield, as in Fig. 2.1.1. Consider the magnetic flux linked between the i<sup>th</sup> conductor and the chield which is taken as reference. From Lenz's law we have

$$\oint_{c} \vec{E} \cdot d\vec{l} = -\frac{d}{dt} \int \vec{B} \cdot d\vec{A} . \qquad (2.1.1)$$

The contour integration is defined in Fig. 2.1.1. If  $\vec{J}$ , the photo Compton current density, is uniform, and normal to the conductor axes, the net flux linked by  $\vec{J}$  is zero, and only the propagation current along the wires,  $I_i$ , contributes to the flux. By definition, each of these will make a contribution to the magnetic flux by an amount  $L_{ij}I_j\Delta z$ , where  $L_{ij}$  is the mutual inductance per unit length of the wires i and j, and  $L_{ii}$  is the self-inductance per unit length of the i<sup>th</sup> wire. Since  $\vec{E}$  is normal to the conductor axis and is also derivable from a scalar potential, the LHS is just

$$V_i + \Delta V_i - V_i \approx \frac{\partial V_i}{\partial z} \Delta z$$
, (2.1.2)

where  $V_{i}$  is the potential of the i<sup>th</sup> wire with respect to reference, and we obtain the first transmission line equation,

$$\frac{\partial V_{i}}{\partial z} = -\sum_{j} L_{ij} \frac{\partial I_{j}}{\partial t} . \qquad (2.1.3)$$

#### Differential Current Transmission Line Equation:

From potential theory the total charge per unit length  $\boldsymbol{Q}_{i}$  on conductor i is given by







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(This expression is derived in Appendix A). Here q is the volume charge density at any instant of time,  $\psi_i(\vec{r})$  is a solution of Laplace's equation with unit potential on conductor i, and zero on the rest. The  $k_{ij}$  are the elements of Maxwell's capacitance matrix, and are obtained by placing a unit potential on each conductor j grounding the rest, solving Laplace's equation, and obtaining the induced charge. Then  $Q_i \equiv k_{ij}$ .

Now, the rate at which charge is deposited in the element  $\Delta z$  on conductor i, is simply the difference between the incoming current  $I_i(z)$  and the outgoing current  $I_i(z+\Delta z)$ , or simply  $-(\partial I/\partial z)\Delta z$ . This is equal to the sum of two terms: (1)  $(\partial Q_i/\partial t)\Delta z$ , which includes both induced and capacitive charge (Eq. 2.1.4), and also (2) the rate of direct charge arrival,  $\Delta z \oint_{C_i} dI_i \vec{J} \cdot \vec{n}_i$ , where  $\vec{n}_i$  is the surface normal directed <u>into</u> the conductor. The result of this is the second transmission line equation

$$\frac{\partial I_{i}}{\partial z} = K_{i} - \sum_{j=1}^{N} k_{ij} \frac{\partial V_{j}}{\partial t} , \qquad (2.1.5)$$

where the source term (i.e., the Norton equivalent current driver) is given by

$$K_{i} = \int d^{2}r \frac{\partial q}{\partial t} \psi_{i} (\vec{r}) - \oint_{c_{i}} dl_{i} \vec{J} \cdot \vec{n}_{i} , \qquad (2.1.6)$$

and  $\partial q/\partial t$  is related to the photo-Compton current via the continuity equation

$$\frac{\partial \mathbf{q}}{\partial \mathbf{t}} = - \vec{\nabla} \cdot \vec{\mathbf{j}} . \tag{2.1.7}$$

By construction  $\vec{J}$  only includes the photo-Compton current, though in principle a conductivity term could be added. Since we have assumed that both  $\vec{J}$  and  $\partial q/\partial t$  follow the radiation pulse, then so do the K.

The transmission line equations (2.1.3) and (2.1.5) may be solved directly, of course, but if conventional circuit analysis codes are to be used, then the equivalent circuit lumped elements of a section of transmission line of length  $\Delta z$  are shown in Fig. 2.1.2. If N is the total number of inner wires, the model consists of N current drivers  $K_i \Delta z$ , N(N+1)/2 capacitances  $C_{ij} \Delta z$ , and twice that many self-and mutual inductances  $1/2L_{ij} \Delta z$ . The elements of Maxwell's capacitance matrix  $k_{ij}$  are related to empirical capacitances  $C_{ij}$  in Fig. 2.1.2 by the relations



Figure 2.1.2 Equivalent circuit model for a multi-conductor transmission line including radiation induced source terms.

$$C_{ij} = -k_{ij}, i \neq j,$$

$$C_{ii} = \sum_{j}^{N} k_{ij}, i = j.$$
(2.1.8)

If the assumption of lossless lines and homogeneous dielectrics is made, then the self and mutual inductances may be obtained by solving the equations

$$\sum_{j=1}^{N} L_{ij}k_{j\ell} = \delta_{i\ell} v^{-2}$$

where v is the velocity of propagation along the cable axis.

## 2.2 MULTICONDUCTOR CABLE GEOMETRY AND PHOTON ATTENUATION

Next, we discuss the details of the incident photon spectrum. Throughout this work we are assuming that there is no time delay in electron-photon transport and that the current drivers, which are the output of this code, are proportional to the instantaneous photon flux. With this in mind the user specifies the instantaneous photon flux F and an energy spectrum. For convenience this could be the peak flux associated with a given pulse. Then when subsequent transmission line codes are driven by the Norton equivalent drivers

Norton driver = peak Norton driver x pulse envelope

where the "pulse envelope" is just the pulse waveform normalized to unity at the peak of the pulse. In addition all results scale with flux, so any convenient unit of flux is appropriate.

The source may have either an arbitrary unnormalized photon energy distribution U(E) or a blackbody distribution of the form

$$U(E) \equiv \frac{E^3}{\exp(E/kT) - 1}$$
 (2.2.1)

Suppose a distribution such as that shown in Fig. 2.2.1 were given.



Figure 2.2.1 Unnormalized photon energy distribution.

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One proceeds to discretize the spectrum by picking out photon energies  $E_{j}$  (the dashed lines in the figure) which are not necessarily uniformly spaced. Then the total unnormalized energy flux would be approximated by

$$\int U(E) dE \approx \sum_{j=1}^{N} U(E_j) \Delta E_j , \qquad (2.2.2)$$

$$\Delta E_{j} \equiv \begin{cases} E_{2} - E_{1}, j = 1, \\ \frac{1}{2} (E_{j+1} - E_{j-1}), j = 2, N - 1, \\ E_{N} - E_{N-1}, j = N. \end{cases}$$
(2.2.3)

Since F is the total energy flux, then the energy flux spectrum  $F(E_i)$  is

$$\mathbf{\dot{F}}(\mathbf{E}_{j}) = \frac{\mathbf{FU}(\mathbf{E}_{j})}{\mathbf{fU}(\mathbf{E}) \ d\mathbf{E}} \approx \frac{\mathbf{FU}(\mathbf{E}_{j})}{\sum_{j=1}^{N} \mathbf{U}(\mathbf{E}_{j}) \ \Delta \mathbf{E}_{j}} \qquad (2.2.4)$$

The number flux spectrum  $N(E_{j})$  is

$$N(E_j) = \frac{F(E_j)}{E_j}$$
, (2.2.5)

and the number flux of photons with energies centered about  $E_i$  is

$$n(E_j) = N(E_j) \Delta E_j$$
 (2.2.6)

The incident photon number spectrum  $n(E_j)$  now must be attenuated through a set of planar shields in front of the cable, and then through the cable itself. It is assumed that exponential attenuation is sufficient to describe the situation; in other words, multiple photon scattering (from Compton scattering) is not important for X-ray spectra of interest (below, say, 300 keV) and neither detailed photon transport has to be taken into account, nor do "buildup factors" have to be included. In brief,

$$\hat{n}(E_{j})^{OUT} = \hat{n}(E_{j})^{IN} \exp[-\mu(E_{j}) \times \text{density } \times \text{g.p.1.} ]$$
 (2.2.7)

where  $\mu$  is the attenuation coefficient and g.p.l. stands for geometrical path length.

First we discuss planar attenuation and its geometry. We had in mind the fact that cables will rarely be directly exposed to radiation but will be shielded somewhat by a side of a box or the skin of the system, for example. Adding attenuators is also a way of hardening the system. For convenience the plane of the incident radiation is normal to the absorbing plane, but the photon direction itself need not be parallel to the absorbing plane's normal. This is shown in Fig. 2.2.2.





The geometrical path length (g.p.1.) is clearly

g.p.1. = t sec 
$$\phi$$
, (2.2.8)

where t is the attenuator thickness and  $\phi$  is the angle that the photon direction makes with the attenuator normal ( $0 \le \phi < 90^\circ$ ).

Next consider the attenuation through the cable itself (Fig. 2.2.3). Let us pick the origin of coordinates as the center of the shield, and the shield axis as the z axis. The photons are considered to be incident in discrete planar sheets, parallel to the x-z plane, and labeled by the coordinate y, the perpendicular distance of the plane to the z axis. The photon's direction in this coordinate system is

$$\vec{n}_{\text{phot}} = \vec{i} \cos \phi - \vec{k} \sin \phi , \qquad (2.2.9)$$

where  $\phi$  has the same meaning as before in our discussion of planar attenuation. What is the geometrical path length of a photon starting at the point  $P_1(x_1, y_1, z_1)$  and arriving at  $P_2(x_2 = y_1, z_2)$ ? Because of the particular choice of axes,  $y_2 = y_1$ , the projection of the geometrical path length onto the x axis is given by

$$g.p.1. = projected g.p.1. x \sec \phi . \qquad (2.2.10)$$

This will be true for any sheet of photons regardless of its coordinate y. The point of this is that we can 1) talk about projected g.p.l.'s exclusively, as if the radiation were normally incident (along the x-axis), and 2) reduce the problem to two dimensions. After calculating the projected g.p.l., we simply have to remember to multiply by sec  $\phi$ .

So now we look at a cross section of a multiconductor cable, as in Fig. 2.2.4. A plane containing the incident photons intersects the cable at coordinate y. The problem of finding the projected path length reduces to 1) finding the x-intersections of the line y with the different interfaces (the dots in the Fig. 2.2.4) and 2) taking the difference between successive intersections. In terms of the notation in the figure, these x-intersections for a fixed y are given by

$$x = \rho \cos \theta \pm \sqrt{\begin{cases} a^2 \\ b^2 \end{cases}} - [y - \rho \sin \theta]^2 \quad . \tag{2.2.11}$$



Figure 2.2.3 Attenuation through the cable.

-

The radius a is to be used for conductor intersections, b for dielectric intersections. (For purposes of calculating attenuation, we ignore gaps). If an intersection is to occur, it occurs in pairs. If the discriminant is negative, no intersection occurs. In summary, we calculate x-intersections via Eq. (2.2.11), calculate the projected path length by taking differences, multiply by sec  $\phi$  to set the full geometrical path length, "remember" what material it is in, look up the appropriate attenuation coefficient, and attenuate the number flux  $n(E_i)$  to that point via Eq. (2.2.7).

For purposes of calculating electron deposition in the dielectric it is necessary to know the direction cosines of the normal to the conductor at the point where the plane (labeled by y) intersects the conductor at x. Assuming the intersection  $\vec{r} \equiv (x,y)$  is known, the conductor normal unit vector satisfies (see Fig. 2.2.4).

$$\vec{n} = \frac{\vec{r} - \vec{\rho}}{a} = \frac{\vec{i}(x - \rho \cos \theta) + \vec{j}(y - \rho \sin \theta)}{a} \equiv \vec{i}\gamma_x + \vec{j}\gamma_y , \qquad (2.2.12)$$

which identifies the direction cosines  $\gamma_x$  and  $\gamma_y$  for interior conductors. For the shield the direction cosines are  $\gamma_x = -x/a$ ,  $\gamma_y = -y/a$  respectively. The angle that the incident photon makes with the conductor normal is

$$\cos^{-1} \stackrel{*}{\underset{\text{phot}}{n}} \cdot \stackrel{*}{\underset{n}{n}} = \cos^{-1} (\gamma_x \cos \phi) , \qquad (2.2.13)$$

where Eqs. (2.2.9) and (2.2.12) have been used.



Figure 2.2.4 Cross-section of a multi-conductor cable. Geometric quantities in the figure represent input to the MCCABE code.

#### 2.3 ELECTRON DEPOSITION

To evaluate Eq. (2.1.6) for the Norton drivers we require the emission current from each conductor surface and the deposited charge profile in the dielectric volume. To obtain this we apply the analytic prescriptions given by Dellin and MacCallum<sup>4)</sup> for the case of a planar interface between two semi-infinite media. While the conductor-dielectric interfaces in real cables are not planar, the distance traveled by electrons is usually much smaller than conductor dimensions, and the planar approximation is reasonable.

The first term in the expression for the Norton driver (Eq. 2.1.6) is the charge deposition term involving  $\partial q/\partial t$ . Since charge deposition occurs in the region surrounding each conductor and does not extend very far into the bulk dielectric, at least for x-rays whose energy is less than 300 keV, it is convenient to break up the volume integration over the entire dielectric into a set of integrations near each conductor surface, i.e.

$$\int d^2 r \frac{dq}{dt} \psi_i \approx \sum_k \oint d\ell_k \int d\eta \frac{dq}{dt} \psi_i$$
(2.3.1)

Here  $d\ell_k$  is a element of arc length about conductor k and n is integrated along the conductor normal from the conductor - dielectric interface into the volume. Dellin and MacCallum have found that the deposition profile exponentially decays away from the interface value, i.e.

$$\frac{dq}{dt} = \sum_{j=1}^{2} \frac{\dot{Q}_{ij}^{(0)2}}{\dot{Q}_{ij}^{(1)}} \exp\left[-\frac{\dot{Q}_{ij}^{(0)}}{\dot{Q}_{ij}^{(1)}}\right]$$
(2.3.2)

All quantities in  $\dot{q}_{ij}^{(0)}$  and  $\dot{q}_{ij}^{(1)}$  are obtained from the QUICKE2 code. However, the emission efficience is  $J^N, J^F$ , and  $J^B$  which in QUICKE2 have the units electrons/photon, are multiplied by  $-|e|\dot{n}$ , where  $\dot{n}$  is the attenuated number flux of photons in Eq. (2.2.7), and  $\dot{q}_{ij}^{(0)}$  has the units of amps/cm<sup>2</sup>. Also, the electron ranges in QUICKE2 which have the units g/cm<sup>2</sup> are converted to cm, and  $\dot{q}_{ij}^{(1)}$  has the units of amps/cm.

The second term in Eq. (2.1.6) is evaluated as

$$\oint d\ell_i \vec{J} \cdot \vec{n}_i = - \int d\ell_i J_i^{\rm I}$$
(2.3.3)

where  $J_{i}^{I}$  is the normal component of the interface current. (The change of sign comes from the fact that  $J_{i}^{I}$  is directed out of the conductor into the dielectric in contrast to  $\dot{n}_{i}$ ).  $J_{i}^{I}$  is easily obtained: the total charge deposition rate is  $\dot{Q}_{i1}^{(0)} + \dot{Q}_{i2}^{(0)}$ , but this must be equal to the difference between current coming into the volume, i.e., the interface current  $J_{i}^{I}$ , and the current leaving it, i.e. the net bulk current,  $J_{i}^{N}$ . We obtain

$$J_{i}^{I} = \sum_{j=1}^{2} \dot{Q}_{ij}^{(0)} + J_{i}^{N}$$
(2.3.4)

where  $J_{i}^{N}$  is taken from QUICKE2 data.

The above expressions apply for the case of mono-energetic incident X-rays. For the case of a distributed source, the full Norton drivers must be built up by superposition. The first index i = 1, 2 indicates the medium in which the deposition occurs and the index 1, 2 indicates the medium in which the electrons are created. The numbers 1 and 2 refer to the media traversed first and second by the X-rays.  $q_{ij}^{(0)}$  represents the total charge deposition rate in the given region, while  $q_{ij}^{(1)}$  is the first moment of it<sup>\*</sup> Dellin and MacCallum give the following expressions for  $q_{ij}^{(0)}$  and  $q_{ij}^{(1)}$ :

$$\dot{Q}_{ij}^{(0)} = \frac{-(-1)^{j} J_{j}^{N} \cos\theta \sqrt{\bar{r}_{j}} - (-1)^{i+j} (J_{j}^{F} + J_{j}^{B}) \sqrt{\bar{r}_{1}\bar{r}_{2}} \sqrt{3/2}}{\sqrt{\bar{r}_{1}} + \sqrt{\bar{r}_{2}}} , \quad (2.3.3)$$

$$\dot{Q}_{ij}^{(1)} = \frac{1}{3} \frac{\bar{r}_{iR_{j}}(\bar{E}_{j})}{\bar{r}_{jR_{j}}(\bar{E}_{j})} \begin{cases} \sqrt{1+1/2 \ S_{3-j}} \\ \sqrt{1+1/2 \ S_{1}} + \sqrt{1+1/2 \ S_{2}} \end{cases} \begin{bmatrix} R_{j}(\bar{E}_{j})\bar{r}_{j}(J_{j}^{F} + J_{j}^{R}) \\ R_{j}(\bar{E}_{j})\bar{r}_{j}(J_{j}^{F} + J_{j}^{R}) \end{bmatrix}$$

$$-\frac{(-1)^{i}R_{j}(\bar{E}_{j})J_{j}^{N}\cos\theta\sqrt{3/2}}{\sqrt{1+1/2}S_{j}} - \delta_{ij}R_{j}(\bar{E}_{j})\bar{r}_{j}(J_{j}^{F} + J_{j}^{B},$$
(2.3.4)

\*In general, there are sets of  $Q_{ij}^{(0)}$  and  $Q_{ij}^{(1)}$  for each electron source type (photo-electric, Auger, Compton), but because of our restruction to photon energies below 300keV where the photo-electric effect dominates, we calculate only one set of the  $Q_{ij}^{(0)}$  and  $Q_{ij}^{(1)}$ .

where

R <sub>i</sub> (E)	= total electron range in the i <sup>th</sup> material at energy E,
Ē	= average energy of electrons created in the i <sup>th</sup> material,
ī,	= ratio of mean vector range to total rnage in the i <sup>th</sup> material,
s <sub>i</sub>	$= 1/\bar{r}_{i} -1,$
$J_{i}^{N}, J_{i}^{F}, J_{i}^{B}$	= the net, forward, and back bulk currents in the i <sup>th</sup> material.
θ	= angle between photon direction and interface normal ( $\leq$ 90°)

#### 2.4 LAPLACE EQUATION IN TWO DIMENSIONS

We present a technique for solving the two-dimensional Laplace equation which takes advantage of the fact that a cross-section of a multiconductor cable shows a collection of arbitrarily placed circles, as in Fig. 2.2.4. Rather than go through the laborious procedure of finite differencing the Laplace equation, we simply write down the formal solution,

$$4\pi\epsilon_{0}\phi(\vec{r}) = \sum_{i=1}^{N} a_{i}\int_{0}^{2\pi} d\theta \sigma_{i}(\theta) \ln \frac{\frac{r^{2}}{a_{0}^{2}} |\vec{r} - \frac{a_{0}^{2}}{r^{2}}\vec{r}|^{2}}{|\vec{r} - \vec{r}|^{2}}, \qquad (2.4.1)$$

where 
$$\vec{r}' = \vec{\rho}_i + \vec{a}_i$$
, and  $\vec{\rho}_i = (\rho_i, \theta_i), \vec{a}_i = (a_i, \theta_i)$ .

The various geometrical quantities are shown in Fig. 2.2.4. But, in this development, we assume that the dielectric is homogeneous and that there are no gaps. The logarithmic term is seen to be the Green's function for a cylinder of radius  $a_0$  which is infinite in length: this guarantees not only that the potential satisfies Laplace's equation, but that it also vanishes on the shield whose radius is  $a_0$ . The unknown charge density  $\sigma_1$  on each conductor includes both free and bound charge (free charge density =  $K\sigma_1$  where K is the dielectric constant near conductor i). Since we are assuming a homogeneous dielectric, there are no dielectric interfaces is discussed below). The first step in obtaining the unknown charge densities is to expand Eq. (2.4.1) in circular harmonics (cos n $\theta$ ', sin n $\theta$ ');

$$4\pi\epsilon_{0}\phi(\vec{r}) = \sum_{i=1}^{N} \sum_{n=0}^{\infty} v_{in}^{+}(\vec{r}) \cdot x_{in}, \qquad (2.4.2)$$

where the spinor  $V_{in}$  is given in Appendix B. The spinor  $X_{in}$  has replaced the unknown charge densities by a set of unknown coefficients,

$$X_{in} = a_{i} \int_{0}^{2\pi} \frac{2\pi}{d\theta \sigma_{i}(\theta)} \left[ \frac{\cos n\theta}{\sin n\theta} \right], \qquad (2.4.3)$$

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the very first one of which yields exactly the induced free charge per unit length  $Q_i = K X_{io}$ . The coefficients X are determined by placing the prescribed potentials  $\nabla_i = \psi(\vec{\rho} + \vec{a}_i), \vec{a}_i = (a_i, \theta),$  on the boundaries, and multiplying Eq. (2.4.2) by  $(4\pi)^{-1} \int_{0}^{2\pi} d\theta$  (cos n $\theta$ , sin n $\theta$ )<sup>+</sup>. This results in the matrix equation

$$2\pi\epsilon_{0}\binom{\delta_{n0} V_{i}}{o} = \sum_{i'=1}^{N} \sum_{n'=0}^{\infty} A_{in}, i'n' X_{i'n'}, \qquad (2.4.4)$$

where the matrix A is given in Appendix B. (In practice the infinite sum over n' is truncated). This procedure determines the capacitance matrix as well.

#### Correction for Non-Homogeneous Dielectric:

Multiconductor cables in practice will not usually have homogeneous dielectrics; contrary to our assumption above, the existence of gaps between insulation and conductors as well as dielectric-dielectric interfaces is the more likely possibility. Our assumption is that non-homogeneities in the dielectric will not affect the capacitance matrix very much (<50%). On the other hand the effect on the potential distribution near conductor-dielectric interfaces is considerable, as will be made clear by the following argument. Consider a parallel plate capacitor whose plate separation is D, but with a small gap d (d<<D) which nonetheless is larger than the range p of an electron penetrating the dielectric. If the dielectric medium were uniform then the potential distribution at X = d +  $p \approx d$ , would be  $\phi/V = d/D$ . However, the presence of a gap (whose dielectric constant was unity) would imply a potential at the same point of  $\phi/V$  = Kd/D, again assuming d<<D. This suggests that for electrons which cross gaps, we calculate the Laplace solution using the formalism of this section where the dielectric constant is that of the dielectric insulation, and then scale the charge profile by multiplying by K. (In principle, of course one can extend the formalism of the last section by demanding the normal component of the displacement vector to be continuous at the dielectricdielectric interface. This would introduce a set of dielectric interface charge densities). The  $\psi_i(\vec{r})$  in Eq. (2.1.6) are obtained by setting  $V_i = 1$  in Eq. (2.4.4) and then using Eq. (2.4.2) to obtain the potential.

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#### 3.0 STRUCTURE AND USE OF THE MCCABE CODE

The MCCABE code was written for use on an interactive, time-share computer system. The code itself consists of four separate subprograms, each of which can be run separately. Briefly, these subprograms accomplish the following:

- 1. FLUXPAK concerns itself with the incident x-ray spectrum and looking up the appropriate photon attenuation coefficients as a function of this energy spectrum.
- ATTNPAK calculates the photon attenuation of the incident spectrum until it reaches conductor/dielectric interfaces.
- 3. CIRCLES calculates the capacitance matrix and solves Laplace's equation.
- 4. DRIVPAK calculates the electron deposition in the dielectric, and the appropriate Laplace equation solutions to obtain the Norton equivalent drivers.

Needless to say, all these subprograms are communicating with each other in a complicated way. Fig. 3.1 gives a flowchart of input and output between the user and the various subprograms. Table 3.1 lists the information contained in each input/output file.

Because of the complicated communication between subprograms we have written the MCHELP code which handles input and program control without the user having to think too much about it. MCHELP is a user-oriented code which interrogates the user and then performs two functions:

- It constructs all necessary input files from user-supplied data on the cable geometry and x-ray environment.
- 2. It sets up a job control file for running the various subprograms.

Fig. 3.2 gives an example of a session between user and MCHELP for the case of a simple coax. The explanatory text provided by MCHELP identifies the variables, and their units, as required by MCCABE. The job file (TAPE44) assumes that the various input files (TAPE5, TAPE3, TAPE15) have been given arbitrary file names and stored in memory. Furthermore, it is assumed that relocatable binary versions of FLUXPAK, ATTNPAK, CIRCLES, and DRIVPAK have been stored under the names BFLUX, BATTN, BCIRCL, and BDRIV, respectively. Fig.3.3 gives the job file produced during the session shown in Fig. 3.2. The output, of this MCCABE run is shown in Fig. 3.4. This problem required 12 CPU seconds on a CDC 6600. Fig. 3.5 lists the input files for a sample three-wire multiconductor cable as produced by MCHELP. Fig. 3.6 gives the output of the CIRCLES and DRIVPAK subprograms of MCCABE which contains the calculated capacitance matrix and Norton drivers. This problem required 87 CPU seconds.

# Table 3.1 Data files used with MCCABE.

Name	Use
TAPE5	input of X-ray spectrum and of cable materials description
TAPE3	input of cable geometry
TAPE15	input to control Laplace equation solution
TAPE6	output of photon cross sections
TAPE4	output of attenuated photon flux at interfaces
TAPE16	output of checks on coefficients of the potential expansion and capacitance matrix calculation
TAPE24	output of electron transport and Norton driver calculation
TAPE8=NSTAB	photon cross section data for FLUXPAK (binary)
TAPE9	photon cross sections selected for ATTNPAK
TAPE27=DELMAC	photo-Compton current data from QUICKE2 for DRIVPAK
TAPE10	photon flux at conductor/dielectric interface for DRIVPAK
TAPE12	coefficients of potential expansions for DRIVPAK



MCHELP 8/3/77 THIS CODE SETS UP INPUT INFO FOR THE MCCABE CODE THE INFO REQUIRED IS DIVIDED INTO 2 PARTS: CABLE GEOMETRY AND SPECTRUM EXECUTION INSTRUCTIONS

THE OUTPUT OF THIS CODE IS A PERFORM FILE(TAPE44) AND VARIOUS FILES WHICH MAY BE SAVED

CABLE GEONETRY AND SPECTRUM

INPUT INFO WHICH YOU GIVE SHOULD FOLLOW NAMELIST RULES WITH END OF ENTRY INDICATED BY \$ IF YOU HAVE INFO IN PERM STORAGE PROVIDE DUMMY INFO OR NOME AT ALL

DO YOU WANT TO CONSTRUCT TAPES FOR FLUXPAK? (1=YES,O=NO) ? 1

PHOTON1 NAMELIST FLUX=FLUX IN CAL/CH2SEC NHIX= NUHBER OF DISTINCT MATERIALS(MAX=10) N= NUMBER OF PHOTON ENERGIES (MAX=50) EPHOT(I),I=1,N ARE PHOTON ENERGIES(KEV) U(I),I=1,N ARE UNNORM. ENERGY SPECTRA(/KEV) IF EQUALLY SPACED ENTER EPHOT(1) AND EPHOT(N) ONLY XKT IS BB TEMP IN KEV(IGNORED IF NOT ENTERED) PHI IS ANGLE(DEGREES) BETWEEN SHIELD NORMAL PROJECTED IN PLANE OF INCIDENT RADIATION AND DIRECTION OF INCIDENT RADIATION (<90 DEG) IPRT=NONZERO GIVES LONG PRINT

\$PHOTON1 ? FLUX=1,N=1,EPHOT=50,U=1,NHIX=4\$ YOU WILL BE ASKED FOR 4

C. B. Salation

MIXTURE NAMELIST FOR EACH MATERIAL(OF UP TO 10 COMPONENTS): THE ORDER OF ENTRY DOES NOT MATTER BUT THE MATERIAL LABEL INDEX WHICH FOLLOWS LATER IN THE INPUT CORRESPONDS TO THIS ORDER OF ENTRY ZA= Z NUMBERS(IN ORDER OF INCREASING Z) WT= WEIGHT FRACTIONS AT=ATOMIC WEIGHT DENSITY=DENSITY(G/CM3) IZDM=Z NO. OF ELEMENT OR LABEL NO. IN DELMAC TABLE

Dielectric type	Label No.
water	901
teflon	902
PVC	903
Mylar	904
Kapton	905
Halar	906
Kel-F	907

Note:

Figure 3.2 Terminal printout from MCHELP for a simple coax.

```
SMIXTURE
? ZA=29, AT=63.54, WT=1, DENSITY=8.9, IZDM=29$
  $NIXTURE
? ZA=6,9.AT=12.01,19.,WT=.24,.76,DENSITY=2.2,IZDM=902$
 SMIXTURE
? ZA=50,AT=118.7,WT=1,DENSITY=7.2,IZDM=50$
  SHIXTURE
? ZA=47.AT=107.9.WT=1.DENSITY=10.5,IZDM=47$
                                                      INPUT TO CIRCLES AND TAPE15 CONSTRUCTION
                                                      MOST INFUT WAS GIVEN IN ATTNPAK FOR CIRCLES
 TAPES HAS BEEN CONSTRUCTED
                                                      PERM NAMELIST
                                                      PER=DIELECTRIC CONSTANT
DO YOU WANT TO CONSTRUCT TAPES AND TAPE15
                                                      MMAX=MAX TERMS IN HARMONIC EXPANSION
FOR ATTNPAK AND CIRCLES? (1=YES,0=NO)
                                                      EPSLN TIMES MIN. DIAG ELEMENT IS LARGEST OFF-DIAG
? 1
                                                       $PERM
                                                     ? PER=2.1, MNAX=1$
 ATTPLN NAMELIST
                                                       TAPE15 HAS BEEN CONSTRUCTED
 NPLANE= NO. OF ATTENUATION PLANES(MAY BE 0)
T(I), I=1, NPLANE = PLANE THICKNESS IN CM
 IPLANLB, I=1,NPLANE=MIXTURE INDICIES
WHICH IS THE ORDER IN WHICH MIXTURES WERE READ
                                                          Note: MMAX=1 is sufficient
 SATTPLN
                                                                  for coaxes. MMAX=4-6
7 $
                                                                  is sufficient for cable
                                                                  bundles depending on
CONDUCT NAMELIST
                                                                  degree of assymetry.
                                                                  EPSLN=0 means no off-
 ALL DISTANCES IN CM, ANGLES IN DEGREES
 NCON=NO. OF COND'S INCLUDING SHIELD
                                                                  diagonal matrix ele-
 TSHIELD=SHIELD THICKNESS
                                                                  ments are discarded
                                                                  before entering sparse
 RADC(I), I=1, NCON ARE COND. RADII
                                                                  matrix routines
 RADD
                  ARE DIELECTRIC RADII
                  ARE GAP SIZES
 GAP
 THE FIRST ENTRY OF RADC, RADD, GAP REFERS TO SHIELD
 HATLBLC(I), I=1, NCON IS THE MATERIAL LABEL INDEX
 MATLBLD(I)
                                                          Note: The flashing modification
 MATLBLF(I)
                                                                  is a phenomenological ad-
 WHERE C IS THE CONDUCTOR, D DIEL., F FLASHING, -
 AND THE LABEL INDEX CORRESPONDS TO
                                                                  justment of the interface
                                                                 current discussed in Refs.
 THE ORDER IN WHICH MIXTURES WERE READ IN ABOVE
 MATBAK IS THE BACKGROUND DIELECTRIC INDEX
                                                                 2 and 7.
 DFLASH(I), I=1, NCON ARE FLASHING THICKNESSES
 RO(I), THET(I), I=1, NCON ARE THE COORDS. OF COND. I
 2 TIMES NY IS THE NO. OF Y PLANES INTERSECTING SHIELD
 IPRT=NONZERO GIVES LONG PRINT
 $CONDUCT
? NCON=2, RO=0,0, NY=10
? MATLBLC=1,1,MATLBLD=2,2,MATBAK=2
? RADC=.1,.0299
? GAP=.005,.001
? RADD=.0651,.065
? TSHIELD=.01
```

TAPE3 HAS BEEN CONSTRUCTED

? MATLBLF=3,4,DFLASH=.0002,.0002\$

Figure 3.2 (continued) Terminal printout from MCHELP for a simple coax.

### EXECUTION INSTRUCTIONS

SHOULD FLUXPAK BE EXECUTED (1=YES.0=NO) ? 1 NAME OF TAPES . Note: These file names ? COAX5 are arbitrary. NAME OF TAPE9 ? COAX9 SHOULD ATTNPAK BE EXECUTED (1=YES,0=NO) ? 1 NAME OF TAPE3 ? COAX3 -NAME OF TAPE9 ? COAX9 NAME OF TAPE10 ? COAX10 -SHOULD CIRCLES BE EXECUTED (1=YES,0=NO) ? 1 NAME OF TAPE15 ? COAX15 -NAME OF TAPE12 ? COAX12 -SHOULD DRIVPAK BE EXECUTED (1=YES,0=NO) ? 1

FILES CONSTRUCTED: TAPE44(PERFORM FILE) TAPE5(INPUT FOR FLUXPAK) TAPE3(INPUT FOR ATTNPAK) TAPE15(INPUT FOR CIRCLES)

LIST TAPE44 TO SEE NAMES ASSIGNED TO DATA FILES REPLACE TAPE5, TAPE3, TAPE15 UNDER THIER NEW NAMES THEN: PERFORM, TAPE44

Figure 3.2 (continued) Terminal printout from MCHELP for a simple coax.

angen and the second

GET, TAPE5=COAX5 GET, TAPE8=NSTAB GET, BFLUX BFLUX, TAPE6=OUTPUT REPLACE, TAPE9=COAX9 GET, TAPE3=COAX3 GET, TAPE9=COAX9 GET, BATTN BATTN, TAPE 4= OUTPUT REPLACE, TAPE 10=COAX10 GET, TAPE15=COAX15 GET, BCIRCL BCIRCL, TAPE 16=OUTPUT REPLACE, TAPE 12=COAX12 GET, TAPE10=COAX10 GET, TAPE12=COAX12 GET, TAPE27=DELMAC GET, BDRIV BDRIV, TAPE26=OUTPUT

Figure 3.3

Job file created by MCCABE for the example given in Figure 3.2.

-

#### 1 FLUXPAK 8/3/77

NO. OF	F MIXTURES		4
FLUX (	CAL/CM2SEC)		1.00000E+00
PHICON	EGREES)		0.
PHOTOM	NS/CAL		5.22600E+14
TOTAL	NFLUX(/CM2	SEC)	5.22600E+14
INDEX	NUMBER FLU.	X(/CM2SEC)	
1 !	5.23E+14		
MIXTU	RE NO./Z NO	./DENSITY/AT	TW DING
1	2.90E+01	8.90E+00	6.35E+01
MIXTU	RE NO./Z NO	./DENSITY/AT	TOMIC WT.
2	8.28E+00	2.20E+00	1.73E+01
MIXTU	RE NO./Z NO	./DENSITY/AT	TONIC WT.
3	5.00E+01	7.20E+00	1.19E+02
HIXTU	RE NO./Z NO	./DENSITY/AT	TONIC WT.
4	4.70E+01	1.05E+01	1.08E+02

1 DRIVPAK 8/3/77

GEOMETRY VARIABLES TRANSFERRED FROM ATTNPAK NCON= 2 RADC= 1.00E-01 2.99E-02 GAP= 5.00E-03 1.00E-03 RADD= 6.51E-02 6.50E-02 RD= 0. 1.00E-07 THET= 0. 0. MATLBLC= 1 1 MATLBLD= 2 2 MATLBLF= 3 4 DFLASH= 2.00E-04 2.00E-04

PHOTON ENERGIES NE= 1 EPHOT= 5.00E+01

TOTAL ENITTED CURRENT FROM SHIELD AND EACH CONDUCTOR ISURF= 8.36E-08 2.40E-08

TOTAL INDUCED CURRENT ON EACH CONDUCTOR DUE TO DEPOSITED CHARGE IAREA= -2.97E-08

NORTON DRIVER TO EACH CONDUCTOR(SHORT CIRCUIT CURRENT) (A/CM) ISC= -5.67E-09

Figure 3.4 MCCABE output for the coax defined in Figure 3.2.

and a second a second

## 1 ATTNPAK 8/3/77

X/Y/X DIR/YDIR/ANGL	E/CON NO.			
ENERGY BIN/NO. FLUX	UNIT LENEO	GTH		
-3.12E-02 -9.50E-02 1 2.78E+13	3.12E-01	9.50E-01	1.25E+00	1
3.12E-02 -9.50E-02	-3.12E-01	9.50E-01	1.89E+00	1
-5.27E-02 -8.50E-02	5.27E-01	8.50E-01	1.02E+00	1
1 1.38E+13 5.27E-02 -8.50E-02	-5.27E-01	8.50E-01	2.13E+00	1
1 1.33E+13	4 415-01	7 505-01	9 495-01	
1 1.16E+13	0.012-01	7.JVE-01	0.402-01	
6.61E-02 -7.50E-02 1 1.10E+13	-6.61E-01	7.50E-01	2.29E+00	1
-7.60E-02 -6.50E-02	7.60E-01	6.50E-01	7.08E-01	1
7.60E-02 -6.50E-02	-7.60E-01	6.50E-01	2.43E+00	1
1 9.81E+12 -8.35E-02 -5.50E-02	8.35E-01	5.50E-01	5.82E-01	1
1 9.70E+12 8.35E-02 -5.50E-02	-8.35F-01	5.50F-01	2.565+00	1
1 9.06E+12	0.075.01			
-8.93E-02 -4.50E-02 1 9.20E+12	8.93E-01	4.50E-01	4.6/E-01	1
8.93E-02 -4.50E-02 1 8-55E+12	-8.93E-01	4.50E-01	2.67E+00	1
-9.37E-02 -3.50E-02	9.37E-01	3.50E-01	3.58E-01	1
9.37E-02 -3.50E-02	-9.37E-01	3.50E-01	2.78E+00	1
1 8.20E+12 -9.68E-02 -2.50E-02	9.68E-01	2.50E-01	2.53E-01	1
1 8.63E+12	-5 405-01	-8 345-01	2 155+00	2
1 2.02E+13	5.472-01	0.302 01	2.132.00	-
1.64E-02 -2.50E-02 1 9.90E+12	5.49E-01	-8.36E-01	9.90E-01	2
9.68E-02 -2.50E-02 1 3.95E+12	-9.68E-01	2.50E-01	2.89E+00	1
-9.89E-02 -1.50E-02	9.89E-01	1.50E-01	1.51E-01	1
-2.59E-02 -1.50E-02	-8.65E-01	-5.02E-01	2.62E+00	2
1 9.53E+12 2.59E-02 -1.50E-02	8.65E-01	-5.02E-01	5.26E-01	2
1 3.09E+12	-0 005-01	1 505-01	2 995400	
1 2.59E+12	-7.872-01	1.502-01	2.772+00	
-9.992-02 -5.00E-03 1 8.42E+12	9.99E-01	5.00E-02	5.00E-02	1
-2.95E-02 -5.00E-03	-9.86E-01	-1.67E-01	2.97E+00	2
2.95E-02 -5.00E-03	9.86E-01	-1.67E-01	1.68E-01	2
9.99E-02 -5.00E-03	-9.99E-01	5.00E-02	3.09E+00	1
1 2.20E+12				

Figure 3.4

(continued) MCCABE output for the coax defined in Figure 3.2

```
1$PHOTON1
   = 1.0,
FLUX
   = 1,
N
   EPHOT
+ 0., 0., 0., 0., 0., 0., 0., 0., 0.,
    0., 0.,
   11
+ 0., 0., 0., 0., 0., 0., 0., 0., 0.,
    0.,
   = 4,
NMIX
   = 0.,
PHI
   = 0.,
XKT
IPRT
   = 0,
$END
1$MIXTURE
   ZA
UT
   AT
   DENSITY = 8.9,
IZDM
   = 29,
$END
1$MIXTURE
ZA
   = 1.0, 6.0, 7.0, 8.0, 0., 0., 0., 0., 0., 0.,
   = 9.41E-03, 5.6091E-01, 1.3082E-01, 2.9886E-01, 0., 0., 0., 0.,
WT
+ 0., 0.,
   = 1.0, 1.2E+01, 1.4E+01, 1.6E+01, 0., 0., 0., 0., 0., 0.,
AT
DENSITY = 1.42,
   = 905,
IZDM
SEND
1SMIXTURE
ZA
   UT
   AT
DENSITY = 7.2,
IZDM
   = 50.
SEND
1SMIXTURE
   ZA
UT
   AT
DENSITY = 1.05E+01,
   = 47,
IZDM
$END
```

Figure 3.5 (a) Input file, TAPE5, for MCCABE created by MCHELP for a 3-wire multi-conductor cable.

```
1SATTPLN
NPLANE = 0,
     T
+ ., 0., 0., 0., 0.,
$END
1$CONDUCT
RADC
    = 1.8E-01, 5.0E-02, 5.0E-02, 5.0E-02, 0., 0., 0., 0., 0., 0., 0
0.,
RADD
     = 1.50001E-01, 6.95E-02, 6.95E-02, 6.95E-02, 0., 0., 0., 0., 0.
+ , 0., 0., 0., 0., 0., 0., 0., 0., 0.,
      0., 0., 0.,
RO
     = 0., 8.03E-02, 8.03E-02, 8.03E-02, 0., 0., 0., 0., 0., 0., 0., 0.,
0.,
THET
     = 0., 6.0E+01, 1.8E+02, 3.0E+02, 0., 0., 0., 0., 0., 0., 0., 0.
GAP
   = 5.0E-03, 1.0E-08, 1.0E-08, 1.0E-08, 0., 0., 0., 0., 0., 0., 0.
0.,
    = 4,
NCON
TSHIELD = 3.3E-02,
+
+ ,
    =10,
NY
MATBAK = C,
MATLBLF =3,4,4,4,
DFLASH=4+2.E-4,
IPRT
     = 0.
$END
```

Figure 3.5 (b) Input file, TAPE3, for MCCABE created by MCHELP for a 3-wire multi-conductor cable.

```
1$NAME1
      = 5.0E-02, 5.0E-02, 5.0E-02, 0., 0., 0., 0., 0., 0., 0., 0., 0.
A
+ , 0., 0., 0., 0., 0., 0., 0., 0.,
      = 1.8E-01,
B
      = 8.03E-02, 8.03E-02, 8.03E-02, 0., 0., 0., 0., 0., 0., 0., 0.,
RH
= 3,
NMAX
       = 4,
XAMM
PER
       = 3.5,
EPSLN
      = 0,
      TH
+ , 0., 0., 0., 0., 0., 0., 0., 0., 0.,
      = 0,
 IPRT
 SEND
```

Figure 3.5 (c) Input file, TAPE15, for MCCABE created by MCHELP for a 3-wire multiconductor cable.

#### 1 CIRCLES 8/3/77

MINIMUM DIAGONAL 1.24996E-01

CAPACI	TANCE	MATRIX(F/CM)
1	1	1.33434E-12
1	2	5.80652E-13
1	3	5.80652E-13
2	1	5.80652E-13
2	2	1.33434E-12
2	3	5.80652E-13
3	1	5.80652E-13
3	2	5.80652E-13
3	3	1.33434E-12

1 DRIVPAK 8/3/77

GEOMETRY VARIABLES TRANSFERRED FROM ATTNPAK NCON= 4 RADC= 1.80E-01 5.00E-02 5.00E-02 5.00E-02 GAP= 5.00E-03 1.00E-08 1.00E-08 1.00E-08 RADD= 1.50E-01 6.95E-02 6.95E-02 6.95E-02 RO= 0. 8.03E-02 8.03E-02 8.03E-02 THET= 0. 6.00E+01 1.80E+02 3.00E+02 MATLBLC= 1 1 1 1 MATLBLD= 2 2 2 2 MATLBLF= 3 4 4 4 DFLASH= 2.00E-04 2.00E-04 2.00E-04 2.00E-04

PHOTON ENERGIES NE= 1 EPHOT= 5.00E+01

TOTAL EMITTED CURRENT FROM SHIELD AND EACH CONDUCTOR ISURF= 6.34E-08 1.38E-08 2.20E-08 1.38E-08

TOTAL INDUCED CURRENT ON EACH CONDUCTOR DUE TO DEPOSITED CHARGE IAREA= -1.73E-08 -2.99E-08 -1.73E-08

NORTON DRIVER TO EACH CONDUCTOR(SHORT CIRCUIT CURRENT) (A/CM) ISC= -3.44E-09 -7.89E-09 -3.44E-09

Figure 3.6 MCCABE output for the three-wire problem defined in Figure 3.5.

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# APPENDIX A REVIEW OF POTENTIAL THEORY

Consider a set of N+1 parallel conductors, the first of which is grounded, separated by a various homogeneous dielectrics. A volume charge density  $\rho(\vec{r})$  is deposited in the dielectric at the points  $\vec{r'}$ . The potential  $\phi$ , the solution of Poisson's equation, and the Green function G satisfy the following:  $\phi$ , G,  $K_{\vec{r}} \frac{\partial \phi}{\partial n}$  and  $K_{\vec{r}} \frac{\partial G}{\partial n}$  are continuous, G=0 on the conductor boundaries, and

$$\nabla^{2} \phi = -\frac{\rho}{\varepsilon K_{r}^{+}}, \quad \nabla^{2} G = -\frac{\delta(\vec{r} - \vec{r}^{-})}{\varepsilon K_{r}^{+}}, \quad (A.1)$$

where  $\varepsilon \xrightarrow{K+}$  is the dielectric constant at the point  $\overrightarrow{r}$ . From Green's theorem,

$$\int d^{2}r \left( \phi \nabla^{2} K_{r} - K_{r} G \nabla^{2} \phi \right) = \int ds \left( \phi \frac{\partial}{\partial n} K_{r} - K_{r} G \frac{\partial \phi}{\partial n} \right)$$
(A.2)

we obtain a representation for  $\phi$ ,

$$\phi(\vec{r}) = \int d^2 r' \rho(\vec{r}') G(\vec{r}' \vec{r}) - \varepsilon_0 \sum_{j=1}^{N+1} V_j \int ds_j K_{\vec{r}_j} \frac{\partial G(\vec{r}, \vec{r})}{\partial n_j} , \quad (A.3)$$

where  $V_j$  is the potential of the j<sup>th</sup> conductor. The normal  $\dot{n}_j$  at the surface whose incremental line element is ds, is directed out of the dielectric volume. A second application of Green's theorem (with G replacing  $\phi$  in Eq. (A.2)) establishes a symmetry of G,

$$G(\vec{rr}') = G(\vec{r}'\vec{r}). \tag{A.4}$$

The induced charge on conductor i is

$$Q_{i} = \varepsilon_{o} \int ds_{i} K_{r_{i}}^{+} \frac{\partial \phi}{\partial n_{i}}$$
$$= \varepsilon_{o} \int ds_{i} K_{r_{i}}^{+} \int d^{2}r \rho(\vec{r}) \frac{\partial G}{\partial n_{i}} (\vec{r})$$

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$$- \varepsilon_{o}^{2} \sum_{j=1}^{N} V_{j} \int ds_{i} \frac{\partial}{\partial n_{i}} K_{\vec{r}_{i}} \int ds_{j} \frac{\partial}{\partial n_{j}} K_{\vec{r}_{j}} G(\vec{r}_{j}\vec{r}_{i}) . \qquad (A.5)$$

We proceed to simplify the interpretation of Eq. (A.5). First we define the capacitance matrix

$$k_{ij} = -\varepsilon_{o}^{2} \int ds_{i} \frac{\partial}{\partial n_{i}} K_{r_{i}} \int ds_{j} K_{r_{j}} \frac{\partial}{\partial n_{j}} G(\vec{r}_{j} \vec{r}_{i}). \qquad (A.6)$$

Next, considered Eq. (A.3) with  $\rho = 0$ , and with all conductors grounded except conductor i which has unit potential. The potential at the point  $\vec{r}$ , which we now call  $\psi_i(\vec{r})$ , satisfies

$$\psi_{i}(\vec{r}') = -\frac{1}{\varepsilon_{o}} \int ds_{i} K_{\vec{r}_{i}} \frac{\partial}{\partial n_{i}} G(\vec{r}_{i}\vec{r}_{o}). \qquad (A.7)$$

This can be inserted into Eq.(A.5) and we have

$$Q_{i} = -\int d^{2}r'\rho(\vec{r}')\psi_{i}(\vec{r}') + \sum_{j=1}^{N} k_{ij} V_{j}.$$
 (A.8)

The first term represents the induced charge, the second the capacitive charge, for the elemental length of cable.

## APPENDIX B:

## EXPLICIT EXPRESSIONS INVOLVED IN LAPLACE SOLUTION

The vectors  $\vec{r} = r$ ,  $\phi$  and  $\vec{\rho} = \rho_i \theta_i$  have the shield center as origin;  $\vec{r}$  is an arbitrary point at which the potential is evaluated,  $\vec{\rho_i}$  is the location of the ith conductor's center with respect to the origin. Define

$$S = \frac{r^{2} \rho_{i}^{2}}{a_{o}^{2}} + a_{o}^{2} - 2 r \rho_{i} \cos (\phi - \theta_{i}),$$
  
$$T = r^{2} + \rho_{i}^{2} - 2r \rho_{i} \cos (\phi - \theta_{i}),$$

$$U = \arctan \frac{r \sin \phi - \rho_i \sin \theta_i}{r \cos \phi - \rho_i \cos \theta_i} .$$

Then

$$V_{in}(\vec{r}) = \begin{cases} \ln S/T, n=0\\ \frac{2}{n} \left(\frac{a_{i}}{\sqrt{T}}\right)^{n} \begin{bmatrix} \cos (nU)\\ \sin (nU) \end{bmatrix} \\ -2 \sum_{m=n}^{\infty} \frac{1}{m} {m \choose n} \left(\frac{r\rho_{i}}{a_{o}^{2}}\right)^{m} \left(\frac{a_{i}}{\rho_{i}}\right)^{n} \begin{bmatrix} \cos ([m-n^{-1}]\theta_{i} - m\phi)\\ -\sin ([m-n^{-1}]\phi_{i} - m\phi) \end{bmatrix}, n \neq 0 \end{cases}$$

Replacing  $\vec{r} \rightarrow \vec{\rho}_i$  and  $\vec{\rho}_i \rightarrow \vec{\rho}_i$ , in S, T and U above, we have for A in, i'n where n=0, n'=0

$$A_{in,i'n'} = \delta_{ii'} \ln \frac{a_0^2 - \rho_i^2}{a_i^a_0} + (1 - \delta_{ii'}) \ln \frac{S}{T};$$

where n>0, n'=0,

$$\begin{split} A_{in,i'n'} &= \frac{1}{2} \sum_{n_1=n}^{\infty} \frac{1}{n_1} {n \choose n} \left( \frac{\rho_i \rho_i}{a_o^2} \right)^{n_1} {a_i \choose \rho_i}^n \begin{bmatrix} -\cos \left( \left[ n_1 - n \right] \theta_i - n_i \theta_i \right) \\ \sin \left( \left[ n_1 - n \right] \theta_i - n_i \theta_i \right) \end{bmatrix} \\ &+ \frac{1}{2n} \left( 1 - \delta_{ii'} \right) \left( \frac{a_i}{\sqrt{T}} \right)^n \begin{bmatrix} \cos \left( n U \right) \\ \sin \left( n U \right) \end{bmatrix} ; \end{split}$$

and where n'>0,

$$A_{\text{in,in}} = \frac{(1 - \delta_{\text{ii}})(1 + \delta_{\text{no}})}{2n} {\binom{-n}{n}} {\binom{\frac{a_{\text{i}}}{\sqrt{T}}}{\sqrt{T}}}^n {\binom{\frac{a_{\text{i}}}{\sqrt{T}}}{\sqrt{T}}}^n {\left[ \cos \left( \left[ n+n^{-1} \right] U \right), \sin \left( \left[ n+n^{-1} \right] U \right) \right]} {\sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right)} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right), -\cos \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right) \right]} {\left[ \sin \left( \left[ n+n^{-1} \right] U \right]} {\left[ \sin \left( n+n^{-1} \right] U \right]} {\left[ \sin$$

$$+\frac{1}{2n}\delta_{nn}\delta_{ii}\begin{bmatrix}1,0\\0,1\end{bmatrix}-\frac{1}{2}(1+\delta_{no})\left(\frac{a_{i}}{\rho_{i}}\right)^{n}\sum_{m=n}^{\infty}\frac{1}{m}\binom{m}{n}\left(\frac{\rho_{i}\rho_{i}}{a_{o}}\right)^{m}\binom{m}{n}\left(\frac{a_{i}}{\rho_{i}}\right)^{n} X$$

$$\left[ \begin{array}{c} \cos \left( \left[ m-n^{\prime} \right] \right. \theta_{i} - \left[ m-n \right] \right. \theta_{i} \right], -\sin \left( \left[ m-n^{\prime} \right] \right. \theta_{i} - \left[ m-n \right] \left. \theta_{i} \right] \\ \sin \left( \left[ m-n^{\prime} \right] \right. \theta_{i} - \left[ m-n \right] \left. \theta_{i} \right], \cos \left( \left[ m-n^{\prime} \right] \right. \theta_{i} - \left[ m-n \right] \left. \theta_{i} \right) \right] \end{array} \right]$$

The coefficient  $\binom{\alpha}{n}$  is defined as  $\binom{\alpha}{n} = \begin{cases} 0 & , n < 0 \\ 1 & , n = 0 \\ \frac{\alpha(\alpha-1) (\alpha-2) \cdots (\alpha-[n-1])}{n!} & , n > 0 \end{cases}$ 

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