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THE MULTIWIRE SHIELDED ARRAY--THEORY AND CODE.(U)

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The Multiwire Shielded Array—Theory and Code

by Michael J. Vrabel

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and Development Command
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A shielded multiwire cable theory is presented in support of the Multiple Systems Evaluation Program (MSEP) goal of characterizing EMP penetration sources for Army tactical systems. The development is supported by a preliminary code and a comprehensive program of experimental testing. An existing cable code provides all system EMP and shield penetration interactions restricting the development to the problems unique in transi-

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) tioning from the single to the multiple wire shielded cable. The approach is based on the solution of the infinite line problem by using electromagnetic theory and a generalization to the finite cable by using electric circuit theory.

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FIGURES

FIGURES (Cont'd)

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1. INTRODUCTION

The Harry Diamond Laboratories (HDL) has been studying electromagnetic pulse (EMP) vulnerability assessment and hardening of critical Army tactical systems under the Multiple Systems Evaluation Program (MSEP). An integral requirement of this program is the development of a sufficient technical base so that a rigorous characterization can be made of all system encountered penetration sources. This report is intended to provide the basis for the development of a multiwire shielded cable capability--a significant and needed program advancement. The results of this effort, the theory, an operational computer code, and a comparison of theory and experimental data are presented.

2. THEORY

The solution to the multiwire shielded cable problem is based on both electromagnetic and electric circuit theory. The approach followed treats the cable as an infinitely long lossless transmission line and solves the resultant problem by using electromagnetic theory. The solution is extended to the finite cable by introducing cable end loading and treating the system as an electric circuit problem. The immediate goal is to reduce the multiwire cable to a Thevenin or Norton equivalent circuit.

A single-wave component on a lossless, infinite transmission line can be written in the standard form

$$I_w = Ie^{j(\omega t-\beta z)} \quad , \tag{1}$$

where I_w is the current representation of the wave. It is a consequence of transmission line theory that the field associated with this wave can be described using steady-state theory. And it is through the judicious application of steady-state theory that the relationship between the current and voltage on a multiwire transmission line can be developed. The wave nature of the signal will be initially disregarded; that is, the treatment will assume $t = 0$ and $z = 0$. This approach permits a simplification of the equations without detracting from their applicability. The wave nature of the signal will be reintroduced at the appropriate point. As is generally the case with all transmission line developments, it is assumed that the minimum wavelength of interest is much longer than the radial dimension of the line.

The Gauss flux law in a dielectric medium is given (in mks units) by

$$\int_{\text{closed } S} \vec{D} \cdot \vec{ds} = \sum_N Q_N \quad . \tag{2}$$

The $\sum_N Q_N$ is the charge within the volume element S and for the geometry to be considered is equal to I/v, where I is the line current and v is the propagation velocity.

The relationship between electric displacement and potential is

$$V = \frac{1}{\varepsilon\varepsilon_0} \int \vec{D} \cdot \vec{dl} \quad . \tag{3}$$

A shielded cable with a single eccentric inner conductor can be treated as two parallel lines by using the method of images. The relationship between cable geometry and line-image position is given by[1]

$$b = \left(a_2^2 - a_1^2 - D^2\right)/D \quad , \tag{4}$$

where

b = wire center to image center distance,

a_2 = coaxial cable inner radius,

a_1 = wire radius,

D = wire center to coaxial cable center distance.

For a wire-image pair with charge per unit length of Q_A and $-Q_A$, from equations (2) and (3) it can be shown that for any point external to the conductors

$$V_A = I_A\left(2\pi\varepsilon^{\frac{1}{2}}\varepsilon_0 c\right)^{-1} \ln\left(\frac{r_2}{r_1}\right) \quad , \tag{5}$$

[1]*R. W. P. King, Transmission Line Theory, McGraw-Hill Book Co., Inc., New York (1955), 34.*

where r_1 and r_2 are the normal radii vectors from conductor centers to the field point.

From the superposition principle, the potential at any field point for a shielded cable composed of an array of NCON wires is

$$V = \sum_{M=1}^{NCON} V_M \quad . \tag{6}$$

For the potentials at the wire surfaces and the shield (the only values of interest), from equations (5) and (6),

$$V_N = \frac{60}{\varepsilon^{\frac{1}{2}}} \sum_{M=1}^{NCON} I_M \ln\left(\frac{r'_{NM}}{r_{NM}}\right) ; \; N = 1, 2, \ldots, NCON + 1, \tag{7}$$

where

r'_{NM} = distance between Nth conductor and image of Mth conductor,

r_{NM} = distance between Nth and Mth conductors--for N = M, r_{NM} = radius of conductor N,

NCON + 1 = shield designation

Redefining terms in equation (7),

$$V_N = \sum_{M=1}^{NCON} Z_{NM} I_M \quad . \tag{8}$$

In cylindrical coordinates, Z_{NM} becomes

$$Z_{NM} = \frac{60}{\varepsilon^{\frac{1}{2}}} \ln\left[\frac{r_N^2 + r^2 - 2r_N r \cos\theta}{r_N^2 + r_M^2 - 2r_N r_M \cos\theta}\right]^{\frac{1}{2}} , \tag{9}$$

where

r_N = radius vector to conductor N,

r = radius vector to image of conductor M,

θ = angle defined by radii vectors to conductors N and M,

r_M = radius vector to conductor M.

From equation (4), the impedance matrix terms, Z_{NM}, can be defined in terms of cable geometry.

Equation (8) is the relationship between wire current and cable potential for the infinitely long multiwire shielded line. To uniquely define both variables, it is necessary to introduce additional conditions on the cable solution to establish either V_N or I_N. The energy per unit cable length of the multiwire shielded cable is

$$U = \frac{\varepsilon^{\frac{1}{2}}}{c} \sum_{N=1}^{NCON} \left(V_N - V_S\right) I_N \quad , \tag{10}$$

where V_S = the potential at the shield. From equation (8),

$$U = \frac{\varepsilon^{\frac{1}{2}}}{c} \sum_{N=1}^{NCON} \sum_{M=1}^{NCON} \left(Z_{NM} - Z_{SM}\right) I_M I_N \quad , \tag{11}$$

where Z_{SM} are the impedance matrix terms for wires M, M = 1, 2, . . . , NCON, to shield. The relative current distribution among the wires is established by requiring that the distribution insure a minimum value for equation (11).

For the array of NCON wires, the impedance to shield for a single wire is

$$ZW_N = \frac{1}{I_N} \sum_{M=1}^{NCON} \left(Z_{NM} - Z_{SM}\right) I_M \quad , \tag{12}$$

where

ZW_N = wire N impedance to shield,

I_N, I_M = relative current on wires N and M.

The impedance of the wire bundle to shield is

$$1/ZW_B = \sum_{N=1}^{NCON} 1/ZW_N \quad , \tag{13}$$

where

ZW_B = wire bundle to shield impedance.

An equivalent single conductor coaxial cable can be defined by requiring

$$ZW_B = \frac{1}{2\pi}\left(\frac{\mu_o}{\varepsilon\varepsilon_o}\right)^{\frac{1}{2}} \ln\left(\frac{b}{a}\right) , \qquad (14)$$

where

μ_o = permeability of free space,

b = inner radius of shield,

a = radius of equivalent inner conductor.

The current on the single conductor coaxial cable, I_T, is related to the current on the multiwire cable by

$$I_T = \sum_{N=1}^{NCON} I_N . \qquad (15)$$

The problem of establishing the absolute values for the wire currents is reduced to establishing the current on a single conductor coaxial cable.

At this point, it is appropriate to introduce cable end loading and, as a consequence, make all variables an explicit function of time. The treatment of the finite length cable requires the introduction of a two-component signal,

$$V_N(t) = V_N^+(t) + V_N^-(t) , \qquad (16)$$

$$I_N(t) = I_N^+(t) - I_N^-(t) . \qquad (17)$$

Although all variables should include a spatial dependence as well as a temporal dependence, since it is the signal at one cable end that is of interest, all terms are assumed to reference this point. By definition, V_N^+ and I_N^+ are identified as V_N and I_M of equation (8) and are independent of cable end loading. The quantities V_N^- and I_N^- are required to insure that the boundary conditions introduced by cable end loading yield the proper value for current (I_N) through and potential (V_N) across all wire loads. The superscripted positive and negative terms can be viewed as being associated with an incident wave and a reflected wave.

If I_T of equation (15) is known, then V_N^+ and I_N^+ are established. Determining the time dependence of I_T is beyond the scope of this work. The theory presented here assumes the availability of a single-conductor coaxial cable code. The intent of this development is to make maximum use of a sophisticated computer code, FREFLD,* available at HDL. By applying FREFLD to the coaxial cable of equation (14) terminated into its characteristic impedance, the time dependence of I_T and thus $V_N^+(t)$ and $I_N^+(t)$ can be calculated.

The potential across an inductor with a series resistance, R, is

$$V_L(t) = L\,\frac{dI(t)}{dt} + RI(t) \quad . \tag{18}$$

Equation (18) can be written in an incremental time form:

$$\int_{t_N}^{t_{N+1}} V_L(t)dt = R\int_{t_N}^{t_{N+1}} I(t)dt + L\int_{t_N}^{t_{N+1}} \frac{dI(t)}{dt}\,dt \quad , \tag{19}$$

$$V_L\left(t_{N+1}\right) = \left(R + \frac{2L}{\Delta t}\right)I\left(t_{N+1}\right) + \left(R - \frac{2L}{\Delta t}\right)I\left(t_N\right) - V_L\left(t_N\right) \quad , \tag{20}$$

where

$\Delta t = t_{N+1} - t_N << 1/f_{max}$,

f_{max} = maximum frequency of interest in final coaxial cable solution.

**FREFLD is a coaxial cable code designed to deal with the multiplicity of coupling problems encountered in an EMP environment. FREFLD represents the work of Robert F. Gray of HDL.*

Similarly, for a capacitor with a series resistance

$$V_C(t) = RI(t) + \frac{Q(t)}{C} \quad , \tag{21}$$

$$V_C\left(t_{N+1}\right) = \left(R + \frac{\Delta t}{2C}\right)I\left(t_{N+1}\right) + \left(-R + \frac{\Delta t}{2C}\right)I\left(t_N\right) + V_C\left(t_N\right) \quad . \tag{22}$$

For a resistor,

$$V_R\left(t_{N+1}\right) = RI\left(t_{N+1}\right) \quad . \tag{23}$$

For an L, an R, or a C network, the potential difference at a time, t_{N+1}, is related to the current and the potential difference at a previous time, T_N, by a relationship of the general form

$$V\left(t_{N+1}\right) = A_1 I\left(t_{N+1}\right) + A_2 I\left(t_N\right) + A_3 V\left(t_N\right) \quad . \tag{24}$$

Although not proven here, the relationship of equation (24) is quite general and can be extended to a number of other circuit elements.

A solution to the finite length multiwire shielded cable problem can now be developed. Initially, all end loading is restricted to terminations obeying the relationship of equation (24), either wire to wire or wire to shield. For an incremental time solution, all quantities that are a function of T_N are known; thus, equation (24) can be written as

$$V_M\left(t_{N+1}\right) = \mathrm{VEE}(M,1)\, I_M\left(t_{N+1}\right) + \mathrm{VEE}(M,2); \; M = 1, 2, \ldots, M_{max} \quad , \tag{25}$$

$$(\mathrm{NCON}/2) \le M_{max} \le \mathrm{NCON} \quad ,$$

where

M = wire load designation,

$$\mathrm{VEE}(M,2) = A_{2M} I_M\left(t_N\right) + A_{3M} V_M\left(t_N\right) \quad .$$

For circuit load M between cable wires A and B, the following boundary conditions hold:

$$I_M(t_{N+1}) = I_A^+(t_{N+1}) - I_A^-(t_{N+1}) = I_B^-(t_{N+1}) - I_B^+(t_{N+1}) \ , \quad (26)$$

$$V_M(t_{N+1}) = V_A^+(t_{N+1}) - V_B^+(t_{N+1}) + V_A^-(t_{N+1}) - V_B^-(t_{N+1}) \ . \quad (27)$$

Two of the NCON set of simultaneous equations that define the multiwire cable solution are, from equations (25) to (27),

$$V_A^+(t_{N+1}) - V_B^+(t_{N+1}) + V_A^-(t_{N+1}) - V_B^-(t_{N+1})$$

$$= \mathrm{VEE}(M,1)\left[I_A^+(t_{N+1}) - I_A^-(t_{N+1})\right] + \mathrm{VEE}(M,2) \ , \quad (28)$$

$$V_A^+(t_{N+1}) - V_B^+(t_{N+1}) + V_A^-(t_{N+1}) - V_B^-(t_{N+1})$$

$$= \mathrm{VEE}(M,1)\left[I_B^-(t_{N+1}) - I_B^+(t_{N+1})\right] + \mathrm{VEE}(M,2) \ . \quad (29)$$

Substituting equation (8) into equation (28) and regrouping terms,

$$\left(Z_{A,1} - Z_{B,1}\right)I_1^-(t_{N+1}) + \left(Z_{A,2} - Z_{B,2}\right)I_2^-(t_{N+1})$$

$$+ \ . \ . \ . \left[Z_{A,A} - Z_{B,A} + \mathrm{VEE}(M,1)\right] I_A^-(t_{N+1})$$

$$+ \ . \ . \ . \left(Z_{A,NCON} - Z_{B,NCON}\right) I_{NCON}^-(t_{N+1})$$

$$= \left(Z_{B,1} - Z_{A,1}\right)I_1^+(t_{N+1}) + \ . \ . \ . \left[Z_{B,A} - Z_{A,A} + \mathrm{VEE}(M,1)\right] I_A^+(t_{N+1})$$

$$+ \ . \ . \ . \left(Z_{B,NCON} - Z_{A,NCON}\right)I_{NCON}^+(t_{N+1}) + \mathrm{VEE}(M,2) \ . \quad (30)$$

All quantities on the right-hand side of the equation are known; the unknowns are $I_1^-(t_{N+1}), \ldots, I_{NCON}^-(t_{N+1})$. If circuit M is tied to the shield ($B \rightarrow NCON + 1$), then equations (28) and (29) reduce to equation (28) only. For a Thevenin or Norton equivalent circuit, the open-circuit voltage and the short-circuit current response of the desired wire or wire-shield pair must be calculated. This calculation requires that the appropriate circuit, M (with associated wire pair L,N or L,NCON + 1), be solved with wire loads R_1 and R_2 satisfying the requirement that

$$R_1 >> \frac{1}{I_L(t)} \sum_{K=1}^{NCON} \left(Z_{L,K} - Z_{N,K}\right) I_K(t) >> R_2 \quad .$$

The development thus far deals with single-wire end loads obeying the relationship of equation (24). Kirchhoff's law can be used to generalize the cable solutions to include wire loads of any arbitrary array of components. At all network nodes (a node is defined in this instance as any network point common to two or more circuit elements with the definition of circuit elements including cable wires), the sum of all branch currents are zero:

$$\sum_n i_n(t) = 0 \quad . \tag{31}$$

The sum of the voltages around any closed loop is zero:

$$v_{ab}(t) + v_{bc}(t) + v_{cd}(t) + v_{da}(t) = 0 \quad . \tag{32}$$

When the loop includes a wire pair or a wire-shield pair, equation (32) becomes

$$v_{ab}(t) + v_{bc}(t) + v_{cd}(t) = V_a(t) - V_d(t) \quad , \tag{33}$$

where a and d designate the conductor pair.

Kirchhoff's law can be used to develop an $n \times n$ array of simultaneous equations to solve for the instantaneous branch currents for any wire loading networks, where n represents the total number of unknown branch currents. It should be recalled from equation (30) that, when the branch represents a cable wire, the branch current solution is for a single component of the wire current, I^-.

At the cable end, the emergence of the wire bundle from the well-defined transmission line geometry and its entry into the random geometry associated with the wire terminations does not eliminate the mutual wire interactions. At the terminations, these interactions can be characterized by the lumped parameter model of mutual inductance.* For two wire circuits with inductances L_A and L_B, the potentials across L_A and L_B are

$$V_A = L_A \frac{di_A}{dt} + K\left(L_A L_B\right)^{\frac{1}{2}} \frac{di_B}{dt} , \tag{34}$$

$$V_B = L_B \frac{diB}{dt} + K\left(L_A L_B\right)^{\frac{1}{2}} \frac{di_A}{dt} . \tag{35}$$

Introducing operational notations, where $p^n \equiv d^n/dt^n$, equations (34) and (35) become

$$V_A = pL_A i_A + pK\left(L_A L_B\right)^{\frac{1}{2}} i_B , \tag{36}$$

$$V_B = pL_B i_B + pK\left(L_A L_B\right)^{\frac{1}{2}} i_A , \tag{37}$$

where K (the coupling coefficient) is a dimensionless parameter with a value obeying $|K| \leq 1$ and is a function of wiring geometry.

Equations (36) and (37) can be rewritten in the general form:

$$V_A = z_{AA} i_A + z_{AB} i_B , \tag{38}$$

$$V_B = z_{BA} i_A + z_{BB} i_B , \tag{39}$$

where

$$z_{AB} = z_{BA} .$$

**To be rigorous, one should include the capacitive coupling terms between all conductors. Cable loading geometry and frequency spectrum rarely permit these terms to be other than insignificant.*

For a cable with m wire load networks ($m \leq NCON$),

$$V_N = \sum_{M=1}^{m} z_{NM} i_M \; ; \; N = 1, 2, \ldots, m \quad , \qquad (40)$$

where

$$z_{NM} = pK_{NM}\left(L_N L_M\right)^{1/2} \quad ,$$

$$K_{NN} = 1,$$

and lowercase letters are used to distinguish the matrix terms of equation (40) from the cable matrix terms of equation (8).

To introduce wire-load mutual inductance into the cable solution matrices, to the network array equations defining the cable end loads must be added equation (40). The most severe problem posed by introducing equation (40) is establishing the value of the coupling coefficients, K_{NM}.

Equation (40) can be rewritten in the form of an incremental time expression:

$$V_K\left(t_{N+1}\right) = \sum_{M=1}^{m} \left[\frac{2K_{KM}}{\Delta t}\left(L_K L_M\right)^{1/2} I_M\left(t_{N+1}\right) - \frac{2K_{KM}}{\Delta t}\left(L_K L_M\right)^{1/2} I_M\left(t_N\right) - V_M\left(t_N\right)\right], \qquad (41)$$

$$V_M\left(t_N\right) = 0 \text{ for } M \neq K \quad .$$

If equation (41) is substituted for the expression given by equation (24), then the special case of inductive wire loads (with both self and mutual inductance effects) can be solved. For a load of the form of equation (41), equation (25) becomes

$$V_A^+(t_{N+1}) - V_B^+(t_{N+1}) + V_A^-(t_{N+1}) - V_B^-(t_{N+1})$$

$$= \sum_{M=1}^{m} \left\{ VEE(M,1)\left[I_M^+(t_{N+1}) - I_M^-(t_{N+1})\right] + VEE(M,2) \right\} . \quad (42)$$

From this expression, the array of simultaneous equations required to solve for I_M^- can be derived in a manner analogous to the derivation of equation (31). For the general loading condition of mutual inductance incidental to a set of arbitrary wire load, Kirchhoff's laws can be introduced as indicated previously.

The development thus far ignores all wire terminations at the far cable end. For a straight cable of physical length L, assuming that the propagation velocity external to the cable is c, the time delays between the initial arrival of the signal at the near end and reflection from the far cable end for three illumination conditions are

$$T_1 = \frac{L}{c}\left(\varepsilon^{1/2} - 1\right) , \quad (43)$$

$$T_2 = \frac{L}{c}\left(\varepsilon^{1/2} + 1\right) , \quad (44)$$

$$T_3 = \frac{L}{c}\,\varepsilon^{1/2} , \quad (45)$$

where

ε = cable dielectric constant,

T_1 = time delay for cable illumination from far end,

T_2 = time delay for cable illumination from near end,

T_3 = time delay for broadside illumination.

These equations represent the maximum time duration for the specified illumination conditions for which the single-end cable solutions are valid. If V_N^A is the potential across load N at cable end A (with a corresponding current I_N^A) and V_N^B is the potential across load M (across the identical conductor pair) at the other cable end, B, then

$$V_N^A(t) = V_N^{A+}(t) + V_N^{A-}(t) + V_N^{B-}(t - T) \quad , \tag{46}$$

$$V_N^B(t) = V_N^{B+}(t) + V_N^{B-}(t) + V_N^{A-}(t - T) \quad , \tag{47}$$

where

$$T = \frac{L}{c} \varepsilon^{\frac{1}{2}} \; ,$$

$$V_N^{B-}(t - T) = V_N^{A-}(t - T) = 0, \text{ for } t < T \; .$$

By introducing the requirements of equations (46) and (47) (or the corresponding relationships between the current components) into the set of simultaneous equations necessary to solve the multiwire problem, a solution can be derived without time duration restrictions.

A common multiwire cable construction technique involves arranging all wires (or twisted wire pairs) on concentric cylindrical layers. This generally involves a different lay for each wire layer. Although all wires preserve their location with respect to all remaining wires on the same layer and with respect to the shield, the distance between wires on different layers becomes a function of location along the cable. The logarithmic relationship between wire distances and the magnitude of the impedance matrix terms Z_{NM} preclude any nearest neighbor approximation in the treatment of the multiwire cable problem. However, as can be seen from equation (7), this logarithmic relationship also insures that the response of any conductor is relatively insensitive to any deviation in the relative positioning of the wires among the layers. If the differential lay among all wire layers is sufficient to insure a full 2π rotation over a cable length shorter than the maximum frequency of interest, then signal averaging can be used to eliminate lay effects. Signal averaging involves a sufficient number of solutions of the simultaneous equation matrix for each value of t_N with a systematic variation in angular position of all wire layers to insure a good approximation to the continuous distribution of wire positions along a cable.

Finally, equation (4) poses a singularity problem for wire coinciding with the cable center. This singularity can be avoided by offsetting the central axis wire.

3. COMPUTER CODE

The multiconductor cable code characterizes the response of a wire pair or a wire-to-shield combination by outputting the open-circuit voltage and short-circuit current. These are sufficient data to develop either a Thevenin or Norton equivalent circuit. All remaining wires must be end loaded with a single R, L-R, or C-R series network. Far-end cable reflections are not included. The code permits the inclusion of from 1 to 59 wires arranged on a maximum of four layers centrosymmetric with respect to the cable axis. These limits can be expanded by minor code modifications. The code contains the user option of wire lay averaging (ROTA = 1) and can be used to establish all the fundamental infinite cable parameters.

To supplement the code comment cards, several additional statements are required.

a. All wires are numbered sequentially from 1 through NCON, starting at the innermost layer (fig. 1).

b. All wire layers are numbered starting from the innermost layer.

c. "MR" designates a single wire number for the desired Thevenin equivalent pair, or the wire number for a wire-shield combination.

d. The shield designation number, LCON, is NCON + 1.

e. The designated load for the MR associated conductor pair must be 50 kΩ.

f. If the conductor of any pair is the shield, its node value must be listed after the wire node number.

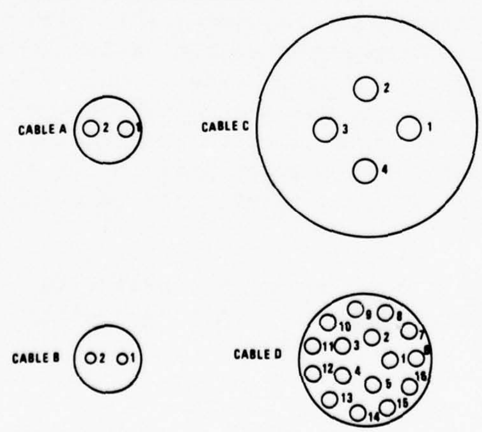

Figure 1. Cross section of shielded multiwire test cables.

Multiconductor cable code

```
      DIMENSION R1(60), R2(60), ANGA(3600), Z(60,60), ZS(60)
      DIMENSION ZP(60,60), RV(4), COEFL(3600), COEFR(60), RN(4)
      DIMENSION CURNT(60), CUR(5), AMP(60), POWER(60), TPOW(8000)
      DIMENSION CUPOS(200), ATIM(200), WIRED(60,200), WIREB(60,200)
      DIMENSION DW(60), CUB(60), DIGIT(200), DIGT(100), DIGA(100)
      DIMENSION ARAY(6000), TERM(600,5), TERMA(600,6), VOLTA(60,5)
      DIMENSION MREG(60), WIREC(60,200), WIREE(60,200), VEE(60,6)
      DIMENSION WIREF(60,200), WIREG(60,200)
      DIMENSION FVOLT(200), FCURR(200), VSHLD(200)
      DIMENSION KREG(60), LREG(60), PCTR(100), SCTR(100)
      DIMENSION XLAB(10), YLAB(10), YLAC(10), YLAD(10)
      DIMENSION PTLAB(20), PTLAC(20), PTLAD(20)
      DIMENSION ZTIME(200), ZTHEV(200), MAR(20)
      DIMENSION BURNT(60), ZZIMP(60), CURR(4,8000), CUA(4), CU(4)
      DIMENSION LZ(4), UP(3), BOT(3), KUP(3), KBOT(3), LRN(4)
      DIMENSION CAPC(50), CAPD(50), PTLAE(10), PTLAF(10), ZAX(10)
      DIMENSION XAX(10), YAX(10), SUBAA(10), XYX(200), YXY(200)
      DIMENSION TYME(200), CURRN(200), VOLTN(200), CURRM(200)
      DIMENSION VEA(60,6), ERF(60), EFR(60), VOLTM(200)
C
      NAMELIST/LISTA/ARAY,LIM,DELT,RV,RN,DW,DC,DI,KK,MR,DIGIT,
     &TOUR,ROTA,XLAB,YLAB,PTLAB,PTLAC,YLAC,MAR,NMAR,YLAD,PTLAD,PLOT,
     &XAX,YAX,SUBAA,CAPC,CAPD,PTLAE,PTLAF,ZAX,BPLOT,TYME
C
      WRITE(6,54)
 54   FORMAT(' A PROGRAM FOR DEVELOPING A THEVENIN EQUIVALENT FOR A MULT
     &IWIRE SHIELDED CABLE UNDER REACTIVE END LOADING CONDITIONS'//)
C
      READ(5,LISTA)
C
C  LAY IS THE LAYER NUMBER TO UNDERGO NO ROTATION
C
C  RV(K)=RADIUS VECTOR TO LAYER K
C
C  RN(K)=NUMBER OF CONDUCTORS IN LAYER K
C
C  DW=INDIVIDUAL WIRE RADIUS
C
C  DC=INNER RADIUS OF COAX SHIELD
C
C  DI=DIELECTRIC CONSTANT
C
C  KK=NUMBER OF WIRE LAYERS
C
C  MR IS THE NUMBER OF THE WIRE FOR WHICH THE THEVENIN EQUIVALENT IS DEVELOPED
C
C
C
      WRITE(6,61)RV
 61   FORMAT(10X,33HRADIUS VECTORS TO WIRE LAYERS ARE/10X,4F6.3//)
      WRITE(6,55)RN
 55   FORMAT(10X,35HNO. OF CONDUCTORS IN EACH LAYER ARE/10X,4F6.0//)
      WRITE(6,56)(DW(I),I=1,60)
 56   FORMAT(10X,29HTHE INDIVIDUAL WIRE RADII ARE/10X,10F6.3//)
      WRITE(6,57)DC
 57   FORMAT(10X,30HINNER RADIUS OF COAX SHIELD IS/10X,F6.3//)
```

```
      WRITE(6,58)DI
58    FORMAT(10X,26HTHE DIELECTRIC CONSTANT IS/10X,F6.3//)
      WRITE(6,59)MR
59    FORMAT(10X,46HWIRE NUMBER FOR THEVENIN EQUIVALENT CIRCUIT IS/10X,I
     &2//)
      WRITE(6,240)
240   FORMAT(' ')
      DO 2 K=1,KK
      KKK=RN(K)
      IF(KKK)1,2,1
1     DO 3 J=1,KKK
      L=1+L
      R1(L)=RV(K)
3     CONTINUE
2     CONTINUE
      L=0
      DO 4 K=1,KK
      KKK=RN(K)
      IF(KKK)6,4,6
6     DO 5 J=1,KKK
      L=1+L
      R2(L)=R1(L)+(DC**2-DW(L)**2-R1(L)**2)/R1(L)
5     CONTINUE
4     CONTINUE
      DO 7 K=1,KK
      COND=COND+RN(K)
7     CONTINUE
      NCON=COND
      DO 426 MG=1,KK
      EGG=EGG+RN(MG)
      AMR=MR
      IF(EGG-AMR)426,425,425
425   LAY=MG
      GO TO 427
426   CONTINUE
427   PI=3.14159
      N=0
      DO 9 K=1,KK
      KKK=RN(K)
      IF(KKK)10,9,10
10    DO 8 M=1,KKK
      N=1+N
      BB=M
      ANGA(N)=2.*PI*(BB-1.)/RN(K)
8     CONTINUE
9     CONTINUE
      DO 13 K=1,NCON
      DO 14 M=1,NCON
      IF(K-M)11,12,11
12    Z(K,M)=(60./DI**0.5)*ALOG((R2(K)-R1(K))/DW(K))
      GO TO 29
11    Z(K,M)=(60./DI**0.5)*ALOG(((R1(K)**2+R2(M)**2-2.*R1(K)*R2(M)*
     &COS(ANGA(K)-ANGA(M)))/(R1(K)**2+R1(M)**2-2.*R1(K)*R1(M)*COS(
     &ANGA(K)-ANGA(M))))**0.5)
29    CONTINUE
14    CONTINUE
13    CONTINUE
      LCON=NCON+1
      DO 15 M=1,NCON
      ZS(M)=(60./DI**0.5)*ALOG(((DC**2+R2(M)**2-2.*DC*R2(M)*
```

```
     &COS(ANGA(M)))/(DC**2+R1(M)**2-2.*DC*R1(M)*COS(
     &ANGA(M))))**0.5)
      Z(LCON,M)=ZS(M)
15    CONTINUE
      DO 16 K=1,NCON
      DO 17 M=1,NCON
      ZP(K,M)=Z(K,M)-ZS(M)
17    CONTINUE
16    CONTINUE
      IF(KK-1)716,717,716
717   DO 718 MM=1,NCON
      CUB(MM)=1./RN(1)
718   CONTINUE
      GO TO 719
716   DO 218 ME=1,4
      IF(RN(ME))218,219,218
219   RN(ME)=1.
218   CONTINUE
      NYC=0
      PICA=1.
419   DO 400 NEM=1,20
      RED1=NEM
      IF(NYC)451,452,451
451   CUR(1)=CU(1)-0.1*(RED1-10.)/PICA
      GO TO 455
452   CUR(1)=2.-0.1*(RED1-1.)
455   IF(2-KK)401,402,402
401   DO 400 NEN=1,20
      RED2=NEN
      IF(NYC)454,458,454
458   CUR(2)=1.-0.1*(RED2-1.)
      GO TO 403
402   CUR(2)=1.-CUR(1)
      GO TO 407
454   CUR(2)=CU(2)-0.1*(RED2-10.)/PICA
403   CONTINUE
      IF(3-KK)404,405,405
404   DO 400 NEP=1,20
      RED3=NEP
      IF(NYC)457,456,457
456   CUR(3)=1.-0.1*(RED3-1.)
      GO TO 406
405   CUR(3)=1.-CUR(1)-CUR(2)
      GO TO 407
457   CUR(3)=CU(3)-0.1*(RED3-10.)/PICA
406   CONTINUE
      CUR(4)=1.-CUR(1)-CUR(2)-CUR(3)
407   CONTINUE
      KM=0
      DO 408 JJ=1,KK
      KKK=RN(JJ)
      DO 408 LL=1,KKK
      KM=1+KM
      AMP(KM)=CUR(KK+1-JJ)/RN(JJ)
408   CONTINUE
      MB=1+MB
      DO 423 MA=1,KK
      CURR(MA,MB)=CUR(KK-MA+1)
423   CONTINUE
      DO 409 NA=1,NCON
```

```
      DO 410 MA=1,NCON
      POWER(NA)=ZP(NA,MA)*AMP(NA)*AMP(MA)+POWER(NA)
410   CONTINUE
409   CONTINUE
      DO 411 NB=1,NCON
      TPOW(MB)=POWER(NB)+TPOW(MB)
      POWER(NB)=0.
411   CONTINUE
400   CONTINUE
      WRITE(6,412)
412   FORMAT('  RELATIVE CURRENT DISTRIBUTION ON SINGLE WIRE OF EACH LAY
     &ER FOR I+ COMPONENT')
      WRITE(6,413)
413   FORMAT('              LAYER 1      LAYER 2      LAYER 3      LAYER 4
     & RELATIVE ENERGY')
      MEE=0
      DO 414 MD=1,10
      POWE=TPOW(1)
      KAPPA=1
      NAT=MB-1
      DO 415 MC=1,NAT
      IF(POWE-TPOW(MC+1))415,415,416
416   POWE=TPOW(MC+1)
      KAPPA=MC+1
415   CONTINUE
      MEE=1+MEE
      TPOW(KAPPA)=1.0E+06
      CU1=CURR(1,KAPPA)/RN(1)
      CU2=CURR(2,KAPPA)/RN(2)
      CU3=CURR(3,KAPPA)/RN(3)
      CU4=CURR(4,KAPPA)/RN(4)
      IF(MEE-1)421,418,421
418   DO 424 MA=1,KK
      CU(MA)=CURR(KK-MA+1,KAPPA)
      CUA(MA)=CURR(MA,KAPPA)/RN(MA)
424   CONTINUE
421   WRITE(6,417)CU1,CU2,CU3,CU4,POWE
417   FORMAT(10X,E10.4,2X,E10.4,2X,E10.4,2X,E10.4,2X,E12.6)
414   CONTINUE
      DO 422 LAR=1,MB
      TPOW(LAR)=0.
422   CONTINUE
      MB=0
      PICA=4.*PICA
      NYC=1
      MAA=1+MAA
      IF(MAA-3)419,419,420
420   CONTINUE
      JA=0
      DO 429 NS=1,KK
      KKK=RN(NS)
      DO 429 MS=1,KKK
      JA=1+JA
      CUB(JA)=CUA(NS)
429   CONTINUE
719   MU=0
      DO 225 KX=1,KK
      MV=RN(KX)
      DO 225  MX=1,MV
      MU=1+MU
```

```
      IF(KX-2)226,227,228
226   CURNT(MU)=CUA(1)
      GO TO 225
227   CURNT(MU)=CUA(2)
      GO TO 225
228   IF(KX-4)229,230,230
229   CURNT(MU)=CUA(3)
      GO TO 225
230   CURNT(MU)=CUA(4)
225   CONTINUE
      MPP=1+MPP
      IF(MPP-1)237,236,237
236   DO 234 JA=1,NCON
      DO 233 KA=1,NCON
      BURNT(KA)=CURNT(KA)
      IF(BURNT(KA))231,232,231
232   BURNT(KA)=1.0E-08
231   ZZIMP(JA)=ZP(JA,KA)*BURNT(KA)/BURNT(JA)+ZZIMP(JA)
233   CONTINUE
      ZZINV=1./ZZIMP(JA)+ZZINV
234   CONTINUE
      ZPOS=1./ZZINV
      WRITE(6,235)ZPOS
235   FORMAT(10X,52HWIRE BUNDLE TO SHIELD IMPEDANCE FOR I+ COMPONENT IS
     &,E10.4//)
237   CONTINUE
      LL=0
      DO 700 NN=1,100
      LL=1+LL
      DIGT(NN)=DIGIT(LL)
      LL=1+LL
      DIGA(NN)=DIGIT(LL)
700   CONTINUE
      MTIM=TDUR/DELT+1.0E-06
      KN=1
      MMTIM=MTIM+1
      DO 701 NN=1,MMTIM
      AA=NN
      DO 704 MM=KN,100
      IF(AA*DELT-DELT-DIGT(MM))703,702,704
702   CUPOS(NN)=DIGA(MM)
      GO TO 711
703   CUPOS(NN)=((DELT*(AA-1.)-DIGT(MM-1))/(DIGT(MM)-DIGT(MM-1)))*
     &(DIGA(MM)-DIGA(MM-1))+DIGA(MM-1)
      GO TO 712
704   CONTINUE
711   KN=MM
      GO TO 800
712   KN=MM-1
800   SS=NN
      TOU=DELT*(SS-1.)
701   CONTINUE
      DO 705 NN=1,MTIM
      AA=NN
      ATIM(NN)=AA*DELT-DELT
705   CONTINUE
      DO 706 NN=1,NCON
      DO 707 MM=1,MTIM
      WIRED(NN,MM)=CUB(NN)*CUPOS(MM)
707   CONTINUE
```

```
 706  CONTINUE
      DO 709 MM=1,MTIM
      DO 708 NN=1,NCON
      DO 710 JJ=1,NCON
      WIREB(NN,MM)=Z(NN,JJ)*WIRED(JJ,MM)+WIREB(NN,MM)
 710  CONTINUE
 708  CONTINUE
 709  CONTINUE
      DO 934 MM=1,MTIM
      DO 938 JJ=1,NCON
      WIREB(LCON,MM)=ZS(JJ)*WIRED(JJ,MM)+WIREB(LCON,MM)
 938  CONTINUE
 934  CONTINUE
C  LIM IS THE TOTAL NUMBER OF COMPONENTS OPERATED UPON + TOTAL NUMBER OF
C  FINAL COMPONENTS
C  ALL LOAD DATA IS READ INTO AN ARRAY: TERM(N,M), N=1,2,...10; M=1,2,...5
C  M ELEMENT #1= COMPONENT TYPE; R=1, C=2, L=3, STOP=4
C            #2= FROM NODE
C            #3= TO NODE
C            #4= COMPONENT VALUE
C            #5= SERIES RESISTANCE
      KT=0
      DO 542 MT=1,LIM
      DO 542 NT=1,5
      KT=1+KT
      TERM(MT,NT)=ARAY(KT)
      WRITE(6,588)TERM(MT,NT)
 588  FORMAT(15X,E10.4)
 542  CONTINUE
      INIA=1
 543  INI=INIA
      IF(LIM-INIA+1)573,565,573
 573  INA=INI+2
      DO 500 N=INI,INA
      M=1
      IF(4.-TERM(N,M))500,501,500
 501  LAST=N-1
 554  INIA=N+1
      GO TO 546
 500  CONTINUE
C  FOR ALL COMPONENTS  V2=C1I2+C2I1+C3V1;  I2=C4V2+C5I1+C6V1 - DATA STORED
C  SERIALLY IN ARRAY TERMA(N,M)  M=1.2,...6
 546  DO 559 N=INI,LAST
      IF(TERM(N,1)-2)511,512,513
 511  TERMA(N,1)=TERM(N,4)
      TERMA(N,2)=0.
      TERMA(N,3)=0.
      TERMA(N,4)=1./TERM(N,4)
      TERMA(N,5)=0.
      TERMA(N,6)=0.
      GO TO 510
 512  TERMA(N,1)=TERM(N,5)+DELT/(2.*TERM(N,4))
      TERMA(N,2)=-TERM(N,5)+DELT/(2.*TERM(N,4))
      TERMA(N,3)=1.
      TERMA(N,4)=1./(TERM(N,5)+DELT/(2.*TERM(N,4)))
      TERMA(N,5)=(TERM(N,5)-DELT/(2.*TERM(N,4)))/
     &(TERM(N,5)+DELT/(2.*TERM(N,4)))
      TERMA(N,6)=-1./(TERM(N,5)+DELT/(2.*TERM(N,4)))
      GO TO 510
 513  TERMA(N,1)=TERM(N,5)+2.*TERM(N,4)/DELT
```

```
      TERMA(N,2)=TERM(N,5)-2.*TERM(N,4)/DELT
      TERMA(N,3)=-1.
      TERMA(N,4)=1./(TERM(N,5)+2.*TERM(N,4)/DELT)
      TERMA(N,5)=(-TERM(N,5)+2.*TERM(N,4)/DELT)/(TERM(N,5)+2.*
     &TERM(N,4)/DELT)
      TERMA(N,6)=1./(TERM(N,5)+2.*TERM(N,4)/DELT)
  510 CONTINUE
  559 CONTINUE
      LASTA=LAST-1
  566 KTD=1+KTD
      DO 567 JK=1,3
      VOLTA(KTD,JK)=TERMA(IN1,JK)
  567 CONTINUE
      DO 593 JK=4,5
      VOLTA(KTD,JK)=TERM(IN1,JK-2)
  593 CONTINUE
      GO TO 543
  565 CONTINUE
C   VEE(1...KTD,1)=C1
C   VEE(1...KTD,2)=C2I1 + C3V1
C   VEE(1...KTD,3)= FROM NODE
C   VEE(1...KTD,4)= TO NODE
C   VEE(1...KTD,5)= TAG LABEL - FROM NODE
C   VEE(1...KTD,6)= TAG LABEL - TO NODE
C   THE REMAINING PART OF THE PROGRAM SOLVES THE SYSTEM OF SIMULTANEOUS
C   LINEAR EQUATIONS RESULTING FROM THE INCLUSION OF WIRE END LOADING
C   ROTA ESTABLISHES LAY AVERAGING EFFECT; 0= NO ROTATION, 1= SINGLE WIRE
C   INCREMENT ROTATION
C   TDUR=TOTAL TIME DURATION OF SIGNAL WAVEFORM
C   DELT=DELTA TIME
      DO 676 MM=1,KTD
      DO 676 NN=3,4
      VEE(MM,NN)=VOLTA(MM,NN+1)
  676 CONTINUE
      DO 627 JQ=1,KTD
      VEE(JQ,1)=VOLTA(JQ,1)
      VEE(JQ,5)=VOLTA(JQ,4)
      VEE(JQ,6)=VOLTA(JQ,5)
      KREG(JQ)=VEE(JQ,3)
      LREG(JQ)=VEE(JQ,4)
  627 CONTINUE
      DO 600 JJ=1,2
      DO 678 IR=2,MTIM
      DO 626 M=1,KTD
      MM=VEE(M,3)
      NN=VEE(M,4)
      IF(JJ-1)946,946,947
  946 VEE(M,2)=VOLTA(M,2)*(WIRED(MM,IR-1)-WIREE(MM,IR-1))+
     &VOLTA(M,3)*((WIREB(MM,IR-1)+WIREC(MM,IR-1))-(WIREB(NN,IR-1)+
     &WIREC(NN,IR-1)))
      GO TO 948
  947 VEE(M,2)=VOLTA(M,2)*(WIRED(MM,IR-1)-WIREF(MM,IR-1))+VOLTA(M,3)*
     &((WIREB(MM,IR-1)+WIREG(MM,IR-1))-(WIREB(NN,IR-1)+WIREG(NN,IR-1)))
  948 CONTINUE
  626 CONTINUE
      IF(ROTA)428,428,675
  428 GO TO 79
  675 KY=0
      DO 459 NN=1,KK
      IF(LAY-NN)460,459,460
```

```
460   KY=1+KY
      LZ(KY)=RN(NN)
      LRN(KY)=NN
459   CONTINUE
      IF(KK-3)461,462,463
463   LZ3=LZ(3)
      DO 80 NA=1,LZ3
      UP(3)=0.
      LRN3=LRN(3)
      DO 464 KA=1,LRN3
      UP(3)=RN(KA)+UP(3)
464   CONTINUE
      BOT(3)=UP(3)-RN(LRN(3))+1.
      KUP(3)=UP(3)
      KBOT(3)=BOT(3)
      KUP3=KUP(3)
      DO 338 MM=1,KTD
      DO 338 NN=5,6
      VEA(MM,NN)=0.
338   CONTINUE
      DO 466 KA=1,KUP3
      IF(KA-KBOT(3))466,467,468
467   DO 469 KB=1,KTD
      IF(UP(3)-VEE(KB,3))470,471,470
470   IF(UP(3)-VEE(KB,4))469,472,469
471   DO 319 MM=1,KTD
      IF(KA-VEE(MM,3))320,321,320
320   IF(KA-VEE(MM,4))319,322,319
321   VEA(MM,5)=VEE(KB,5)
      GO TO 466
322   VEA(MM,6)=VEE(KB,5)
      GO TO 466
319   CONTINUE
472   DO 323 MM=1,KTD
      IF(KA-VEE(MM,3))324,325,324
324   IF(KA-VEE(MM,4))323,326,323
325   VEA(MM,5)=VEE(KB,6)
      GO TO 466
326   VEA(MM,6)=VEE(KB,6)
      GO TO 466
323   CONTINUE
469   CONTINUE
468   DO 473 KB=1,KTD
      BL=KA-1
      IF(BL-VEE(KB,3))475,474,475
475   IF(BL-VEE(KB,4))473,476,473
474   DO 330 MM=1,KTD
      IF(KA-VEE(MM,3))331,332,331
331   IF(KA-VEE(MM,4))330,333,330
332   VEA(MM,5)=VEE(KB,5)
      GO TO 466
333   VEA(MM,6)=VEE(KB,5)
      GO TO 466
330   CONTINUE
476   DO 334 MM=1,KTD
      IF(KA-VEE(MM,3))335,336,335
335   IF(KA-VEE(MM,4))334,337,334
336   VEA(MM,5)=VEE(KB,6)
      GO TO 466
337   VEA(MM,6)=VEE(KB,6)
```

```
      GO TO 466
334   CONTINUE
473   CONTINUE
466   CONTINUE
      DO 339 MM=1,KTD
      DO 339 NN=5,6
      IF(VEA(MM,NN))340,339,340
340   VEE(MM,NN)=VEA(MM,NN)
339   CONTINUE
462   LZ2=LZ(2)
      DO 80 NB=1,LZ2
      UP(2)=0.
      LRN2=LRN(2)
      DO 238 KA=1,LRN2
      UP(2)=RN(KA)+UP(2)
238   CONTINUE
      BOT(2)=UP(2)-RN(LRN(2))+1.
      KUP(2)=UP(2)
      KBOT(2)=BOT(2)
      DO 316 MM=1,KTD
      DO 316 NN=5,6
      VEA(MM,NN)=0.
316   CONTINUE
      KUP2=KUP(2)
      DO 263 KA=1,KUP2
      IF(KA-KBOT(2))263,241,242
241   DO 243 KB=1,KTD
      IF(UP(2)-VEE(KB,3))244,245,244
244   IF(UP(2)-VEE(KB,4))243,246,243
245   DO 300 MM=1,KTD
      IF(KA-VEE(MM,3))301,302,301
301   IF(KA-VEE(MM,4))300,303,300
302   VEA(MM,5)=VEE(KB,5)
      GO TO 263
303   VEA(MM,6)=VEE(KB,5)
      GO TO 263
300   CONTINUE
246   DO 304 MM=1,KTD
      IF(KA-VEE(MM,3))305,306,305
305   IF(KA-VEE(MM,4))304,307,304
306   VEA(MM,5)=VEE(KB,6)
      GO TO 263
307   VEA(MM,6)=VEE(KB,6)
      GO TO 263
304   CONTINUE
243   CONTINUE
242   DO 247 KB=1,KTD
      BL=KA-1
      IF(BL-VEE(KB,3))248,249,248
248   IF(BL-VEE(KB,4))247,250,247
249   DO 308 MM=1,KTD
      IF(KA-VEE(MM,3))309,310,309
309   IF(KA-VEE(MM,4))308,311,308
310   VEA(MM,5)=VEE(KB,5)
      GO TO 263
311   VEA(MM,6)=VEE(KB,5)
      GO TO 263
308   CONTINUE
250   DO 312 MM=1,KTD
      IF(KA-VEE(MM,3))313,314,313
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313   IF(KA-VEE(MM,4))312,315,312
314   VEA(MM,5)=VEE(KB,6)
      GO TO 263
315   VEA(MM,6)=VEE(KB,6)
      GO TO 263
312   CONTINUE
247   CONTINUE
263   CONTINUE
      DO 317 MM=1,KTD
      DO 317 NN=5,6
      IF(VEA(MM,NN))318,317,318
318   VEE(MM,NN)=VEA(MM,NN)
317   CONTINUE
461   LZ1=LZ(1)
      DO 80 NC=1,LZ1
      UP(1)=0.
      LRN1=LRN(1)
      DO 265 KA=1,LRN1
      UP(1)=RN(KA)+UP(1)
265   CONTINUE
      BOT(1)=UP(1)-RN(LRN(1))+1.
      KUP(1)=UP(1)
      KBOT(1)=BOT(1)
      KUP1=KUP(1)
      DO 357 MM=1,KTD
      DO 357 NN=5,6
      VEA(MM,NN)=0.
357   CONTINUE
      DO 267 KA=1,KUP1
      IF(KA-KBOT(1))267,268,269
268   DO 270 KB=1,KTD
      IF(UP(1)-VEE(KB,3))271,272,271
271   IF(UP(1)-VEE(KB,4))270,273,270
272   DO 341 MM=1,KTD
      IF(KA-VEE(MM,3))342,343,342
342   IF(KA-VEE(MM,4))341,344,341
343   VEA(MM,5)=VEE(KB,5)
      GO TO 267
344   VEA(MM,6)=VEE(KB,5)
      GO TO 267
341   CONTINUE
273   DO 345 MM=1,KTD
      IF(KA-VEE(MM,3))346,347,346
346   IF(KA-VEE(MM,4))345,348,345
347   VEA(MM,5)=VEE(KB,6)
      GO TO 267
348   VEA(MM,6)=VEE(KB,6)
      GO TO 267
345   CONTINUE
270   CONTINUE
269   DO 274 KB=1,KTD
      BL=KA-1
      IF(BL-VEE(KB,3))275,276,275
275   IF(BL-VEE(KB,4))274,277,274
276   DO 349 MM=1,KTD
      IF(KA-VEE(MM,3))350,351,350
350   IF(KA-VEE(MM,4))349,352,349
351   VEA(MM,5)=VEE(KB,5)
      GO TO 267
352   VEA(MM,6)=VEE(KB,5)
```

```
      GO TO 267
349   CONTINUE
277   DO 353 MM=1,KTD
      IF(KA-VEE(MM,3))354,355,354
354   IF(KA-VEE(MM,4))353,356,353
355   VEA(MM,5)=VEE(KB,6)
      GO TO 267
356   VEA(MM,6)=VEE(KB,6)
      GO TO 267
353   CONTINUE
274   CONTINUE
267   CONTINUE
      DO 358 MM=1,KTD
      DO 358 NN=5,6
      IF(VEA(MM,NN))359,358,359
359   VEE(MM,NN)=VEA(MM,NN)
358   CONTINUE
79    CONTINUE
      L=0
      DO 601 M=1,NCON
      DO 602 K=1,KTD
      KFOLD=VEE(K,5)
      LFOLD=VEE(K,6)
      IF(KFOLD-1-NCON)616,602,616
616   L=1+L
      IF(M-KFOLD)604,603,604
603   COEFL(L)=Z(KFOLD,M)-Z(LFOLD,M)+VEE(K,1)
      GO TO 602
604   COEFL(L)=Z(KFOLD,M)-Z(LFOLD,M)
602   CONTINUE
      DO 605 K=1,KTD
      KFOLD=VEE(K,5)
      LFOLD=VEE(K,6)
      IF(LFOLD-1-NCON)617,605,617
617   L=1+L
      IF(M-LFOLD)606,607,606
607   COEFL(L)=Z(KFOLD,M)-Z(LFOLD,M)-VEE(K,1)
      GO TO 605
606   COEFL(L)=Z(KFOLD,M)-Z(LFOLD,M)
605   CONTINUE
601   CONTINUE
      L=0
      DO 608 M=1,KTD
      KFOLD=VEE(M,5)
      LFOLD=VEE(M,6)
      IF(KFOLD-1-NCON)618,608,618
618   L=1+L
      MREG(L)=KFOLD
      COEFR(L)=WIREB(LFOLD,IR)-WIREB(KFOLD,IR)+VEE(M,1)*WIRED(KFOLD,IR)
     &+VEE(M,2)
608   CONTINUE
      DO 609 M=1,KTD
      KFOLD=VEE(M,5)
      LFOLD=VEE(M,6)
      IF(LFOLD-1-NCON)610,609,610
610   L=1+L
      MREG(L)=LFOLD
      COEFR(L)=WIREB(LFOLD,IR)-WIREB(KFOLD,IR)-VEE(M,1)*WIRED(LFOLD,IR)
     &+VEE(M,2)
609   CONTINUE
```

```
      EPS=1.0E-07
      CALL GELG(COEFR,COEFL,NCON,1,EPS,IER)
      DO 361 MM=1,KTD
      KZA=VEE(MM,3)
      IF(KZA-NCON-1)362,363,362
 362  KZB=VEE(MM,5)
      EFR(KZA)=COEFR(KZB)
 363  KZC=VEE(MM,4)
      IF(KZC-NCON-1)364,361,364
 364  KZD=VEE(MM,6)
      EFR(KZC)=COEFR(KZD)
 361  CONTINUE
      DO 365  MM=1,NCON
      COEFR(MM)=EFR(MM)
 365  CONTINUE
      IF(JJ-2)633,634,634
 633  PCTR(IR)=1.+PCTR(IR)
      DO 621 M=1,NCON
      WIREE(M,IR)=COEFR(M)+WIREE(M,IR)
 621  CONTINUE
      GO TO 80
 634  SCTR(IR)=1.+SCTR(IR)
      DO 714 M=1,NCON
      WIREF(M,IR)=COEFR(M)+WIREF(M,IR)
 714  CONTINUE
 80   CONTINUE
      IF(JJ-1)925,925,926
 925  CONTINUE
      DO 811 MM=1,NCON
      WIREE(MM,IR)=WIREE(MM,IR)/PCTR(IR)
 811  CONTINUE
      DO 624 M=1,NCON
      DO 625 MM=1,NCON
      WIREC(M,IR)=Z(M,MM)*WIREE(MM,IR)+WIREC(M,IR)
 625  CONTINUE
 624  CONTINUE
      DO 942 MM=1,NCON
      WIREC(LCON,IR)=ZS(MM)*WIREE(MM,IR)+WIREC(LCON,IR)
 942  CONTINUE
      GO TO 678
 926  CONTINUE
      DO 812 MM=1,NCON
      WIREF(MM,IR)=WIREF(MM,IR)/SCTR(IR)
 812  CONTINUE
      DO 636 M=1,NCON
      DO 637 MM=1,NCON
      WIREG(M,IR)=Z(M,MM)*WIREF(MM,IR)+WIREG(M,IR)
 637  CONTINUE
 636  CONTINUE
      DO 944 MM=1,NCON
      WIREG(LCON,IR)=ZS(MM)*WIREF(MM,IR)+WIREG(LCON,IR)
 944  CONTINUE
C  WIREB(1...NCON,1...MTIM) CONTAINS V+
C  WIRED(1...NCON,1...MTIM) CONTAINS I+
C  WIREC(1...NCON,1...MTIM) CONTAINS V- FOR A LOAD OF 50K OHMS ON WIRE MR
C  WIREE(1...NCON,1...MTIM) CONTAINS I- FOR A LOAD OF 50K OHMS ON WIRE MR
C  WIREF(1...NCON,1...MTIM) CONTAINS I- FOR A LOAD OF 0.01 OHMS ON WIRE MR
C  WIREG(1...NCON,1...MTIM) CONTAINS V- FOR A LOAD OF 0.01 OHMS ON WIRE MR
 678  CONTINUE
      DO 903 MM=1,KTD
```

```
      IF(MR-KREG(MM))904,905,904
904   IF(MR-LREG(MM))903,905,903
905   JMR=MM
      GO TO 906
903   CONTINUE
906   IF(JJ-2)631,632,632
631   VEE(JMR,1)=0.01
      GO TO 600
632   VEE(JMR,1)=50000.
600   CONTINUE
C  MAR IS THE WIRE NUMBER FOR WHICH CURRENT IS DESIRED
C  NMAR IS THE TOTAL WIRE COUNT FOR MAR
      IF(NMAR)547,547,550
550   DO 547 M=1,NMAR
      DO 548 MM=1,MTIM
      MMAR=MAR(M)
      WCURR=WIRED(MMAR,MM)-WIREF(MMAR,MM)
      WVOLT=WIREB(MMAR,MM)+WIREC(MMAR,MM)-WIREB(LCON,MM)-WIREC(LCON,MM)
      XCURR=WIRED(MMAR,MM)-WIREE(MMAR,MM)
      XVOLT=WIREB(MMAR,MM)+WIREG(MMAR,MM)-WIREB(LCON,MM)-WIREG(LCON,MM)
      IF(NMAR-1)374,375,374
375   CURRN(MM)=WCURR
      VOLTN(MM)=WVOLT
      CURRM(MM)=XCURR
      VOLTM(MM)=XVOLT
374   WRITE(6,549)MMAR,MM,WCURR
549   FORMAT(7X,29HCURRENT THROUGH LOAD ON WIRE ,I3,19HFOR TIME INCREMEN
     &T ,I3,3HIS ,E10.4)
548   CONTINUE
547   CONTINUE
      DO 680 MM=1,MTIM
      DO 681 NN=1,NCON
      VSHLD(MM)=ZS(NN)*(WIRED(NN,MM)+WIREE(NN,MM))+VSHLD(MM)
681   CONTINUE
680   CONTINUE
      DO 907 MM=1,KTD
      IF(MR-KREG(MM))909,908,909
909   IF(MR-LREG(MM))907,910,907
907   CONTINUE
910   IF(KREG(MM)-NCON)720,720,918
908   IF(LREG(MM)-NCON)912,912,911
720   DO 721 NN=1,MTIM
      FVOLT(NN)=WIREB(MR,NN)+WIREC(MR,NN)-WIREB(KREG(MM),NN)-
     &WIREC(KREG(MM),NN)
      FCURR(NN)=WIRED(MR,NN)-WIREF(MR,NN)
      WRITE(6,914)NN,FVOLT(NN),FCURR(NN)
721   CONTINUE
      GO TO 921
912   DO 913 NN=1,MTIM
      FVOLT(NN)=WIREB(MR,NN)+WIREC(MR,NN)-WIREB(LREG(MM),NN)-
     &WIREC(LREG(MM),NN)
      FCURR(NN)=WIRED(MR,NN)-WIREF(MR,NN)
      WRITE(6,914)NN,FVOLT(NN),FCURR(NN)
914   FORMAT(2X,43HTHEVENIN EQUIVALENT VOC FOR TIME INCREMENT ,I3,
     &4H IS ,E10.3,29H- - THE CORRESPONDING ISX IS ,E10.3)
913   CONTINUE
      GO TO 921
911   DO 915 NN=1,MTIM
      FVOLT(NN)=WIREB(MR,NN)+WIREC(MR,NN)-VSHLD(NN)
      FCURR(NN)=WIRED(MR,NN)-WIREF(MR,NN)
```

```
      WRITE(6,917)NN,FVOLT(NN),FCURR(NN)
  917 FORMAT(2X,43HTHEVENIN EQUIVALENT VOC FOR TIME INCREMENT ,I3,4H IS
     &,E10.3,29H- - THE CORRESPONDING ISX IS ,E10.3)
  915 CONTINUE
      GO TO 921
  918 DO 919 NN=1,MTIM
      FVOLT(NN)=WIREB(MR,NN)+WIREC(MR,NN)-WIREB(KREG(MM),NN)-
     &WIREC(KREG(MM),NN)
      FCURR(NN)=WIRED(MR,NN)-WIREF(MR,NN)
      WRITE(6,920)NN,FVOLT(NN),FCURR(NN)
  920 FORMAT(2X,43HTHEVENIN EQUIVALENT VOC FOR TIME INCREMENT ,I3,4H IS
     &,E10.3,29H- - THE CORRESPONDING ISX IS E10.3)
  919 CONTINUE
C   FVOLT(1...MTIM) IS THE FINAL VOLTAGE ACROSS LOAD AT MR
C   FCURR(1...MTIM) IS THE FINAL CURRENT THROUGH LOAD AT MR
C   VSHLD(1...MTIM) IS THE SHIELD POTENTIAL
  921 CONTINUE
      DO 949 N=1,MTIM
      IF(FCURR(N))951,950,951
  950 FCURR(N)=1.0E-12
  951 ZTHEV(N)=FVOLT(N)/FCURR(N)
      WRITE(6,952)N,ZTHEV(N)
  952 FORMAT(2X,25HZTHEV FOR TIME INCREMENT ,I3,4H IS ,E10.3)
  949 CONTINUE
      DO 953 N=1,MTIM
      DD =N
      ZTIME(N)=DELT*(DD-1.)
  953 CONTINUE
C   DRAW1, DRAW2, AND DRAW3 ARE PLOT ROUTINES
      CALL DRAW2 (1,8,8,20,0,MTIM,0.,2.,XLAB,YLAD,PTLAD,SUBLAD,ZTIME,
     &CUPOS)
      CALL DRAW2 (1,8,8,20,0,MTIM,0.,2.,XLAB,YLAB,PTLAB,SUBLAB,ZTIME,
     &FVOLT)
      CALL DRAW2 (1,8,8,20,0,MTIM,0.,2.,XLAB,YLAC,PTLAC,SUBLAC,ZTIME,
     &FCURR)
      IF(PLOT)366,367,371
  366 CALL DRAW1(1,8,8,20,0,MTIM,0.,2.,XLAB,YLAD,PTLAD,SUBLAD,ZTIME,
     &CUPOS)
      CALL DRAW1(1,8,8,20,0,MTIM,0.,2.,XLAB,YLAB,PTLAB,SUBLAB,ZTIME,
     &FVOLT)
      CALL DRAW1(1,8,8,20,0,MTIM,0.,2.,XLAB,YLAC,PTLAC,SUBLAC,ZTIME,
     &FCURR)
      GO TO 367
  371 IF(BPLOT)376,373,372
  373 CALL DRAW3(1,1,6,6,9,9,XAX,YAX,PTLAE,SUBAA)
      CALL DRAW3(2,1,1,23,2,2,TYME,CAPC,1.E-30,0.)
      CALL DRAW3(2,1,1,MTIM,0,0,ZTIME,FCURR,0.,0.)
      CALL DRAW3(3,1,0,0,0,-200,XYX,YXY,0.,0.)
      CALL DRAW3(1,2,6,6,9,9,XAX,ZAX,PTLAF,SUBAA)
      CALL DRAW3(2,2,1,23,2,2,TYME,CAPD,1.E-30,0.)
      CALL DRAW3(2,2,1,MTIM,0,0,ZTIME,FVOLT,0.,0.)
      CALL DRAW3(3,2,0,0,0,200,XYX,YXY,0.,0.)
      GO TO 367
  376 CONTINUE
  372 CONTINUE
  367 CONTINUE
      WRITE(6,1003)
 1003 FORMAT(' WIRE DELT     V+      V- (50K)      I+      I- (50K)  V- (.01
     &)  I- (.01)   VSHLD')
      IF(MTIM-5)368,368,369
```

```
368   M5=1
      GO TO 370
369   M5=5
370   DO 1000 N=1,LCON
      DO 1001 M=1,MTIM,M5
      WRITE(6,1002)N,M,WIREB(N,M),WIREC(N,M),WIRED(N,M),WIREE(N,M),
     &WIREG(N,M),WIREF(N,M),VSHLD(M)
1002  FORMAT(2H  ,I2,3H   ,I2,1H ,7E10.2)
1001  CONTINUE
1000  CONTINUE
      WRITE(6,76)
76    FORMAT('  NOTE...ALL UNITS FOR PRINTED VALUES ARE VOLTS, AMPERES O
     &R OHMS')
      STOP
      END
```

4. COMPARISON OF CODE AND EXPERIMENTAL RESULTS

Four shielded cables were used for all tests. Figure 1 is a scaled illustration of the cross-section geometry of the cables, and table I is a list of the relevant parameters. All geometrical parameters were obtained from either the manufacturer's data or physical measurements.

TABLE I. TEST CABLE PARAMETERS

Parameter	Cable			
	A	B	C	D
Wire count	2.0	2.0	4.0	16.0
Wire radii	0.019	0.011	0.032	0.019
Shield radius	0.081	0.081	0.25	0.159
Dielectric constant	2.25	2.25	5.5	2.25
Wire layer radii	0.041	0.041	0.1	0.060 0.125

For the multiwire line, cable impedance is a function of the driving mode and, unlike the single conductor coaxial cable, can be altered by the cable end terminations. Treating the infinitely long line, for the four-wire cable of figure 1, from equation (8),

$$V_1 = Z_{11}i_1 + Z_{12}i_2 + Z_{13}i_3 + Z_{14}i_4 \quad ,$$

$$V_2 = Z_{21}i_1 + Z_{22}I_2 + Z_{23}i_3 + Z_{24}i_4 \quad ,$$

$$V_3 = Z_{31}i_1 + Z_{32}i_2 + Z_{33}i_3 + Z_{34}i_4 \quad ,$$

$$V_4 = Z_{41}i_1 + Z_{42}i_2 + Z_{43}i_3 + Z_{44}i_4 \quad ,$$

$$V_S = Z_{S1}i_1 + Z_{S2}i_2 + Z_{S3}i_3 + Z_{S4}i_4 \quad ,$$

where V_N and i_N, N = 1, 2, 3, 4, are the voltage and the current for wire N, and subscript S references the shield. If the cable is driven in a balanced mode, that is, for $i_1 = i_2 = -i_3 = -i_4$ and $i_S = 0$,

$$Z_{12,34} = \frac{V_1 - V_3}{2i_1} = Z_{11} - Z_{13} \quad , \tag{48}$$

where $Z_{12,34}$ is the cable impedance for the balanced driving mode. For the condition that $i_1 = i_3 = -i_2 = -i_4$ and $i_S = 0$,

$$Z_{13,24} = Z_{11} + Z_{13} - 2Z_{12} \quad . \tag{49}$$

For $i_1 = -3i_2 = -3i_3 = -3i_4$ and $i_S = 0$,

$$Z_{1,234} = \frac{4}{3}\left(Z_{11} - Z_{12}\right) \quad . \tag{50}$$

If the four wires are driven to shield, that is, $i_1 = i_2 = i_3 = i_4 = -i_S/4$, then

$$Z_{1234,S} = \left(Z_{11} + 2Z_{12} + Z_{13} - 4Z_{S1}\right)/4 \quad . \tag{51}$$

Similarly, for the two-wire shielded cable for the balanced driving mode,

$$Z_{1,2} = 2Z_{11} - 2Z_{12} \quad . \tag{52}$$

For the two wires driven to shield,

$$Z_{12,S} = \left(Z_{11} + Z_{12} - 2Z_{S1}\right)/2 \quad . \tag{53}$$

For the 16-wire, two-layer cable of figure 1, for the conditions that $i_M = i_N$ for M,N = 1, 2, . . . , 5, $i_J = i_K$ for J,K = 6, 7, . . ., 16,

$$\sum_{N=1}^{5} i_N = - \sum_{N=6}^{16} i_N \quad , \; i_S = 0 \quad ,$$

$$Z_{1,\ldots 5,6\ldots 16} = \frac{1}{5}\sum_{N=1}^{5}\left(Z_{1N} - Z_{6N}\right) + \frac{1}{11}\sum_{N=6}^{16}\left(Z_{6N} - Z_{1N}\right) \quad . \tag{54}$$

For $i_M = i_N = 0$, M,N = 1, 2, . . ., 5,

$$i_J = i_K = -i_S/11, \; J,K = 6, 7, \ldots, 16 \quad ,$$

$$Z_{6\ldots 16,S} = \frac{1}{11}\sum_{N=6}^{16}\left(Z_{6N} - Z_{SN}\right) \quad . \tag{55}$$

For $i_M = i_N = -i_S/5$, $M,N = 1, 2, \ldots, 5$,

$$i_J = i_K = 0, \; J,K = 6, 7, \ldots, 16,$$

$$Z_{1\ldots5,S} = \frac{1}{5} \sum_{N=1}^{5} \left(Z_{1N} - Z_{SN}\right) \; . \tag{56}$$

If the cable coupling is the EMP mode of through-the-shield signal penetration, then the impedance of the infinitely long line is given by equation (13) with the auxiliary conditions given in section 2. For the two- and four-wire cables, this relationship reduces to equations (53) and (51). Table II is a tabulation of the experimentally determined cable impedances, $Z_{N,M}$, and the corresponding values as calculated from data generated by the multiwire cable code.

In section 2, the requirement is imposed that, for the infinitely long cable, the signal penetration results in a wire current distribution that represents a minimum energy density. The consequence of this requirement is demonstrated by calculating the ratio of the current on a single inner layer wire to a single outer layer wire for the two-layer cable of figure 1 as the number of outer layer wires is reduced from 11 to 1: the remaining wires are uniformly distributed about the outer layer circumference. The results are plotted in figure 2. The sign reversal observed between the inner and outer layers is typical of dense, multilayer cables. An investigation of three- and four-layer cables shows a similar current reversal between adjacent layers.

Figure 3 is a schematic of the cable driver designed to test the predictions of the cable code. A significant design deficiency is the inability to measure the wire bundle current prior to cable end interaction. To arrive at $I_T^+(t)$, a required input to the multiwire code, certain inferences based on code results must be made. Under resistive cable end loading, the measured waveforms at the wire terminations have a shape matching that of $I_T^+(t)$ for the period prior to the arrival of the far-end cable reflection. For short-circuit terminations to shield for the wire bundle, the current at any termination is double the corresponding value of $I^+(t)$. An examination of the experimental data reveals that the signal coupled through the shield is not a smooth waveform and that the noise level is sufficient to preclude any precise determination of its shape. For the latter reason, a smooth waveform intended only to approximate the general shape of the measured data was used with the code.

TABLE II. EXPERIMENTAL AND THEORETICAL CABLE IMPEDANCE TERMS

Cable	Term	Impedance (Ω)	
		Experimental	Theoretical
A	$Z_{1,2}$	76	70
	$Z_{12,S}$	26	28
B	$Z_{1,2}$	128	118
	$Z_{12,S}$	40	39
C	$Z_{12,34}$	38	39
	$Z_{13,24}$	28	28
	$Z_{1,234}$	47	44
	$Z_{1234,S}$	18	21
D	$Z_{1...5,6...16}$	21	24
	$Z_{6...16,S}$	7.8	7.8
	$Z_{1...5,S}$	29	35

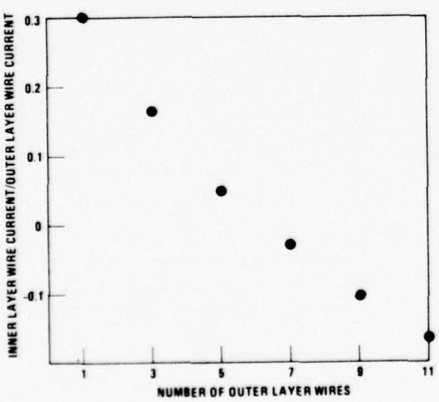

Figure 2. Current reversal on two-layer cable.

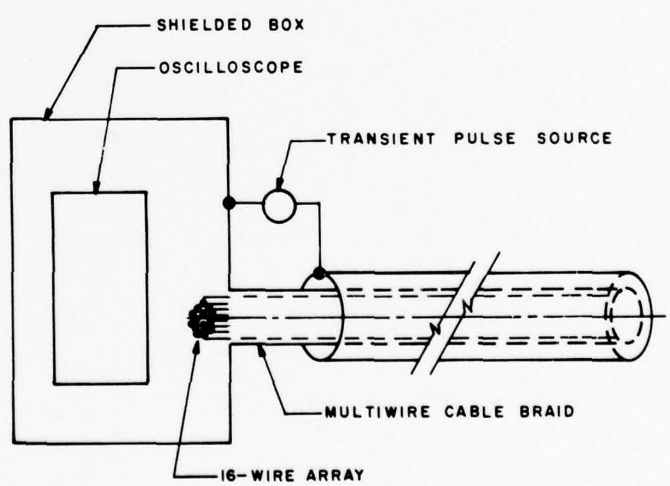

Figure 3. Cable-driver configuration.

The magnitudes of all experimental and theoretical data are related by normalizing the experimental results to a peak driving current of 1 A. The results are normalized by scaling the experimental data for the case of short-circuit wire bundle termination to 2 A. A comparison of the code and the experimental results for a single inner and a single outer layer wire to shield is given in figures 4 and 5 for the case of all wires short-circuited to shield. The open-circuit voltage measurement represents the wire to shield open-circuit voltage for the indicated wire with all remaining conductors short-circuited. The effect of termination lead inductance is shown in figure 6, a set of current measurements employing a short-circuit termination lead length of approximately 10 cm. A similar set of data is presented in figures 7 and 8 for the other extreme in cable end loading--all wires in open-circuit termination. A comparison of the waveform data for the two extremes in termination conditions reveals the significance of the wire end loading in determining the signal. Tables III and IV list the experimental peak amplitude response of all inner layer and four outer layer wires for the loading conditions noted. These data are supplemental to information contained in figures 4 through 8 and indicate the general level of response variability from wire to wire.

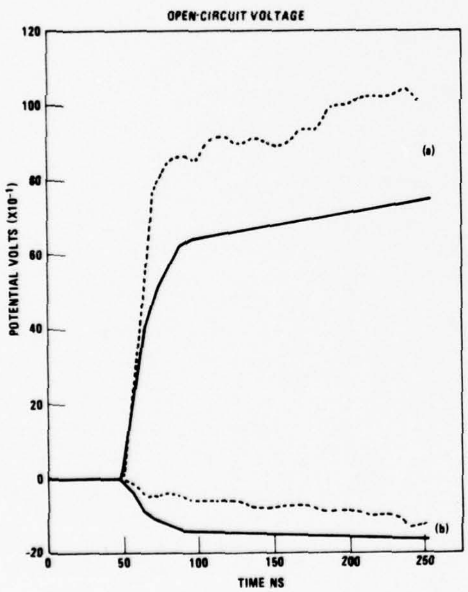

Figure 4. Wire-to-shield potential for (a) single outer and (b) single inner layer wires for 16-conductor cable with remaining wires short-circuited to shield (experimental ..., theoretical——).

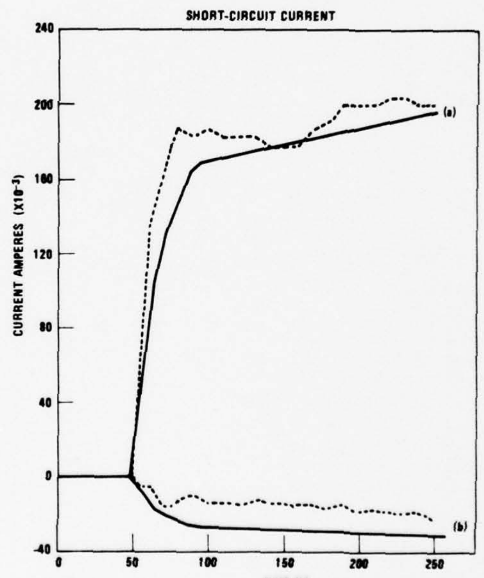

Figure 5. Current on (a) single outer and (b) single inner layer wires for 16-conductor cable with all wires short-circuited to shield (experimental ..., theoretical ——).

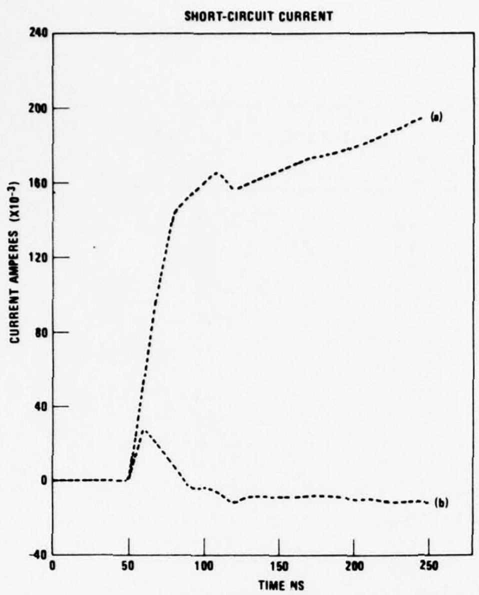

Figure 6. Experimental wire current to shield corresponding to data of figure 5, but with increased termination inductance: (a) single outer layer and (b) single inner layer wire responses.

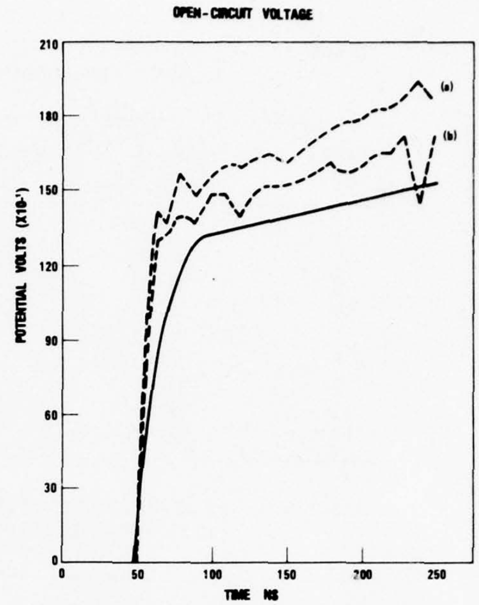

Figure 7. Wire-to-shield potential for (a) single outer and (b) single inner layer wires for 16-conductor cable (two theoretical curves superimposed) for all wires into open-circuit termination (experimental ..., theoretical ——).

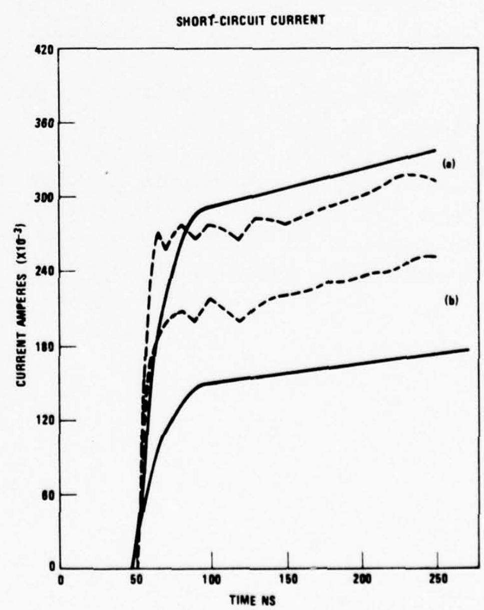

Figure 8. Current on (a) single outer and (b) single inner layer wires short-circuited to shield for 16-conductor cable with all other wires open-circuit termination (experimental ..., theoretical ——).

TABLE III. PEAK AMPLITUDE RESPONSE OF 16-WIRE CABLE UNDER SHORT-CIRCUIT END-LOADING CONDITIONS

Wire No.	Open-circuit voltage (V_{OC}) (V)	Short-circuit current (I_{SX}) (mA)	V_{OC}/I_{SX} (Ω)
1	1.0	18	56
2	1.05	19	55
3	0.70	13	54
4	0.40	7	57
5	0.65	12	54
6	11.0	220	50
9	10.0	190	53
11	9.5	195	49
13	10.0	180	56

TABLE IV. PEAK AMPLITUDE RESPONSE OF 16-WIRE CABLE UNDER OPEN-CIRCUIT END-LOADING CONDITIONS

Wire No.	Open-circuit voltage (V_{OC}) (V)	Short-circuit current (I_{SX}) (mA)	V_{OC}/I_{SX} (Ω)
1	16.5	225	73
2	16.5	225	73
3	16.5	225	73
4	17.0	230	74
5	17.0	230	74
6	19.0	305	62
9	18.0	295	61
11	17.5	295	59
13	17.0	280	61

To avoid the difficulties inherent in the cable-driver design of figure 3, the configuration of figure 9 was used to drive, in this instance, the four-wire cable of figure 1. The effect of distributed series cable resistance is compensated for in the $I^{+}(t)$ driving waveform. The open-circuit voltage and the short-circuit current are given in figures 10 to 15 for a single wire to shield with each remaining wire identically terminated with capacitors (0.1 μF, 1500 pF, or 80 pF).

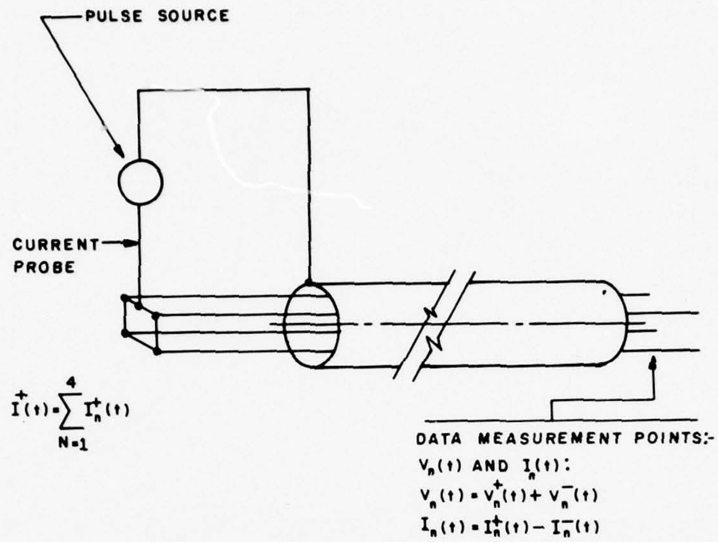

Figure 9. Modified cable-driver test configuration to permit measurement of all $I^+(t)$ current components.

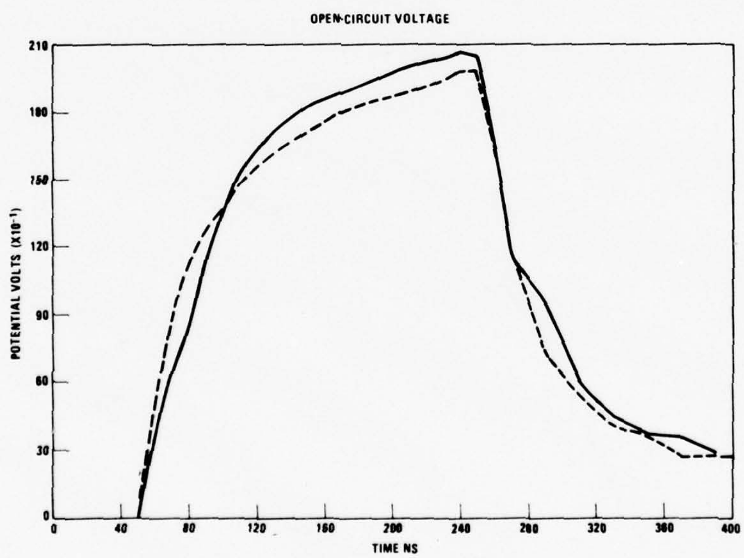

Figure 10. Single-wire potential to shield for four-wire cable with remaining wires terminated to shield with 0.1-μF capacitors (experimental ..., theoretical ——).

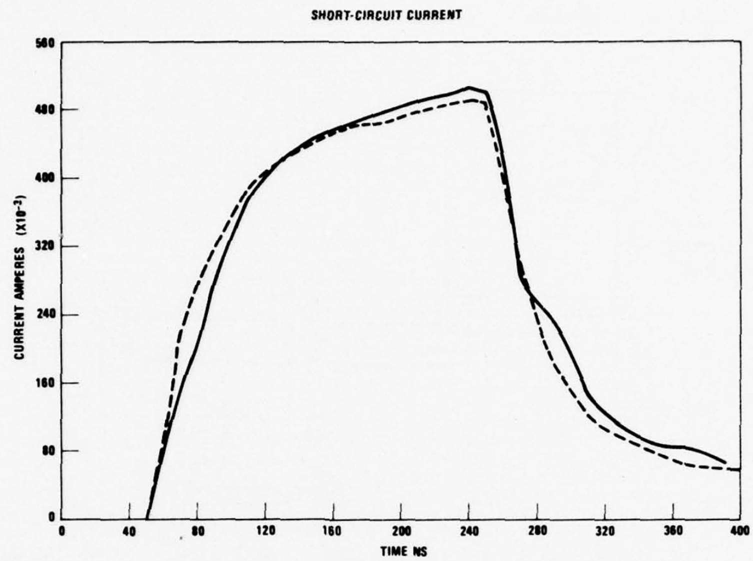

Figure 11. Single-wire current to shield for four-wire cable with remaining wires terminated to shield with 0.1-μF capacitors (experimental ..., theoretical ——).

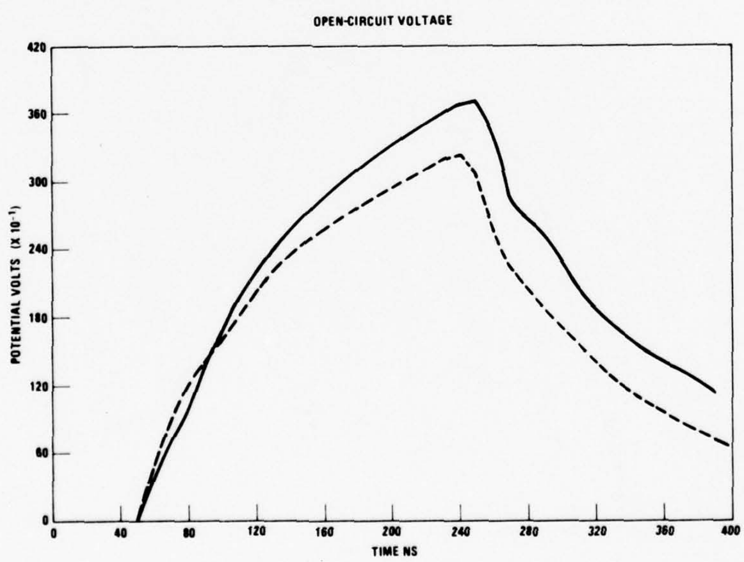

Figure 12. Single-wire potential to shield for four-wire cable with remaining wires terminated to shield with 1500-pF capacitors (experimental ..., theoretical ——).

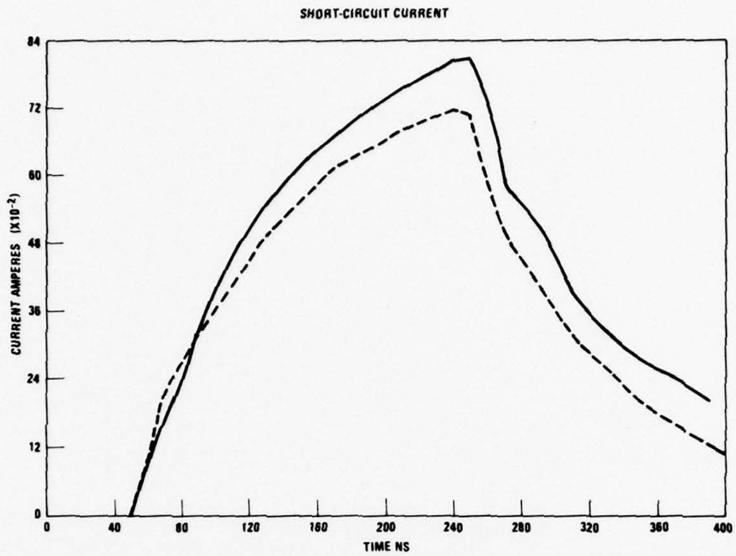

Figure 13. Single-wire current to shield for four-wire cable with remaining wires terminated to shield with 1500-pF capacitors (experimental ..., theoretical ——).

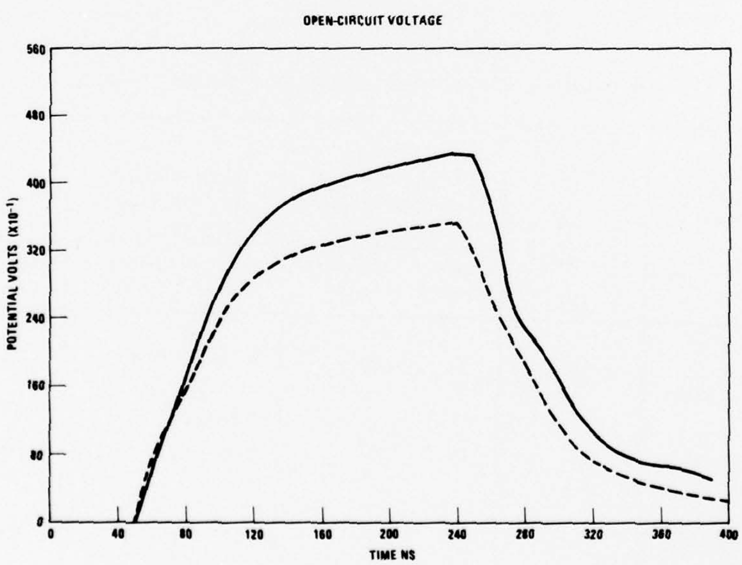

Figure 14. Single-wire potential to shield for four-wire cable with remaining wires terminated to shield with 82-pF capacitors (experimental ..., theoretical ——).

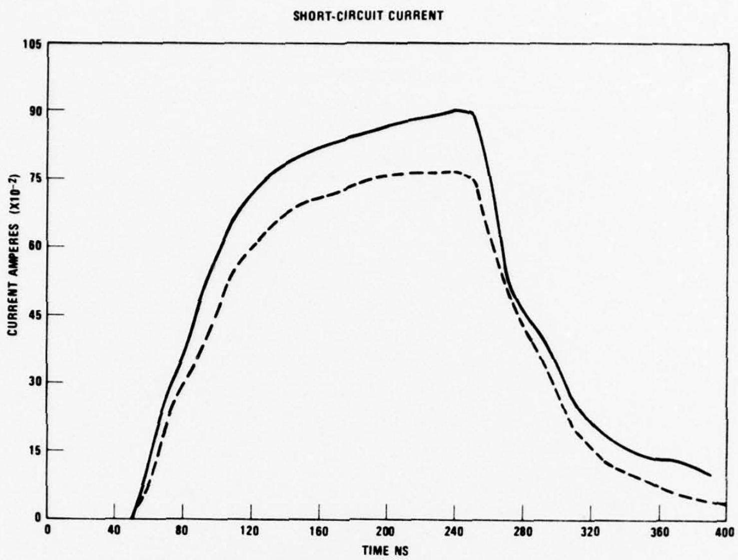

Figure 15. Single-wire current to shield for four-wire cable with remaining wires terminated to shield with 82-pF capacitors (experimental ..., theoretical ——).

An exhaustive series of tests was performed with the four-wire cable under resistive end loading. Since the impedance of a resistive load is independent of frequency, no wave shape distortion is incurred, and all data can be tabulated by magnitude. Table V is representative of the resistively loaded cable results.

TABLE V. FOUR-WIRE CABLE RESPONSE UNDER RESISTIVE END LOADING

Measured conductor pair	Remaining wire loads (Ω)	Drive current. $I^+ = \sum_{N=1}^{4} i_N^+$ (A)	Open-circuit voltage (V_{OC}) (V)		Short-circuit current (I_{SX}) (A)		V_{OC}/I_{SX} (Ω)	
			Experimental	Theoretical	Experimental	Theoretical	Experimental	Theoretical
1-S	2-S = 0 3-S = 0 4-S = open	1	25	27	0.56	0.62	45	44
1-S	2-S = 0 3-S = open 4-S = 0	1	20	21	0.47	0.52	43	40
1-S	2-S = open 3-S = open 4-S = open	1	36	44	0.75	0.90	48	49
1-S	2-S = 0 3-S = 0 4-S = 0	1	20	20	0.48	0.50	42	40
1-2	3-S = 0 4-S = open	1	4.2	4.9	-	0.074	-	66

A similar series of tests was performed with the two-layer cable under resistive end loading by using the configuration of figure 9. The multiwire cable code was modified to permit the imposition of an arbitrary I^+ current component on all wires, and a resistor network was added to the pulse generator to permit the injection of an identical current on all wires. This is a contrived current distribution, not at all related to the conditions demonstrated by figure 2 for a through-the-shield coupling condition and as such does not relate to what can be anticipated under an EMP. Nevertheless, the results obtained are useful for testing all provisions of the multiwire cable code, except for the algorithm that establishes the I^+ distribution. The results are given in table VI. A series of curves was generated for the two-layer cable under resistive end loading (fig. 16 to 20). These represent the measured and predicted voltages across a single-wire load to shield ranging in value from a short-circuit to an open-circuit termination.

Table VII compares the code-predicted source impedance and the point on curves where the load voltage is half the open-circuit value (the experimental source impedance).

Table VIII lists the experimental and theoretical responses of the cable of figure 1(a) under the loading conditions indicated.

TABLE VI. SIXTEEN-WIRE CABLE RESPONSE UNDER RESISTIVE END LOADING

Measured conductor pair	Remaining wire loads (Ω)	Drive current $I^+ = \sum_{N=1}^{16} i_N^+$ (A)	Open-circuit voltage (V_{OC}) (V)		Short-circuit current (I_{SX}) (A)		V_{OC}/I_{SX} (Ω)	
			Experi-mental	Theoret-ical	Experi-mental	Theoret-ical	Experi-mental	Theoret-ical
1-S	2 . . . 5-S = 0 6 . . . 10-S = 39 11 . . . 16-S = open	1	9.1	10.0	0.18	0.18	51	56
1-S	2 . . . 5-S = 0 6 . . . 16-S = open	1	10.2	11.6	0.20	0.21	51	56
5-S	1 . . . 4-S = 0 6 . . . 10-S = 0 11 . . . 16-S = open	1	8.6	8.4	0.17	0.15	51	56

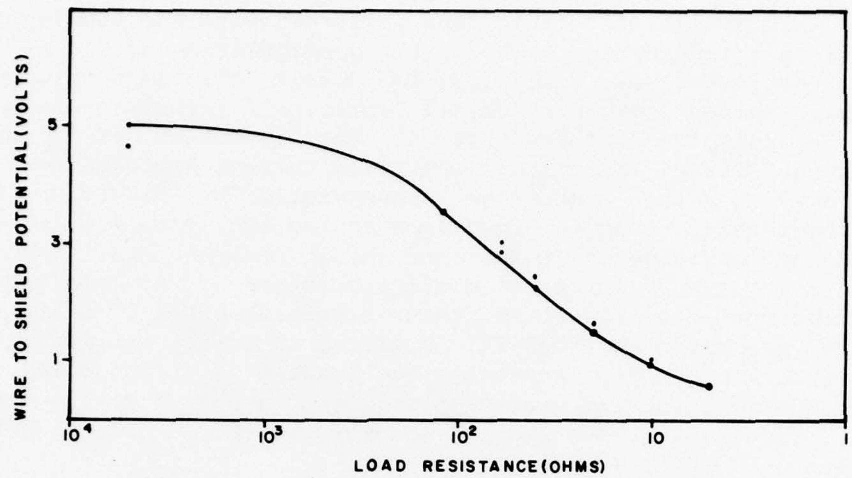

Figure 16. Wire 6 response for 16-wire cable with remaining wires short-circuited to shield (experimental ——, theoretical ...).

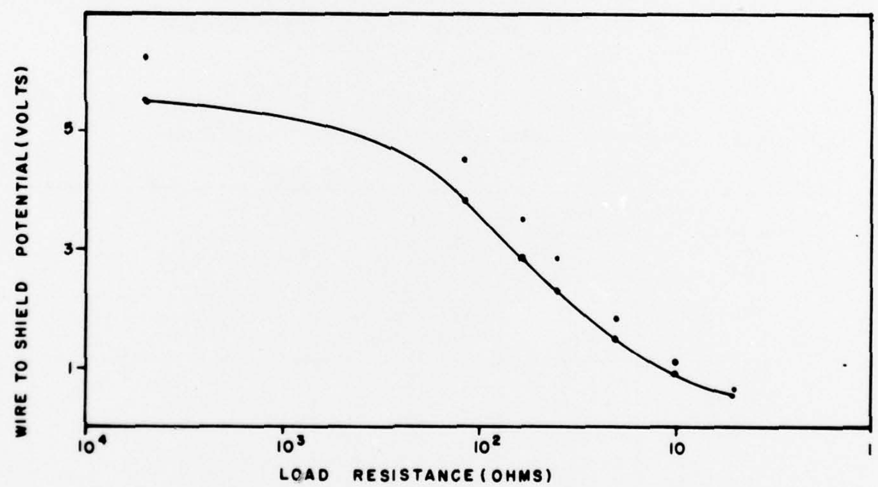

Figure 17. Wire 1 response for 16-wire cable with remaining wires short-circuited to shield (experimental ——, theoretical ...).

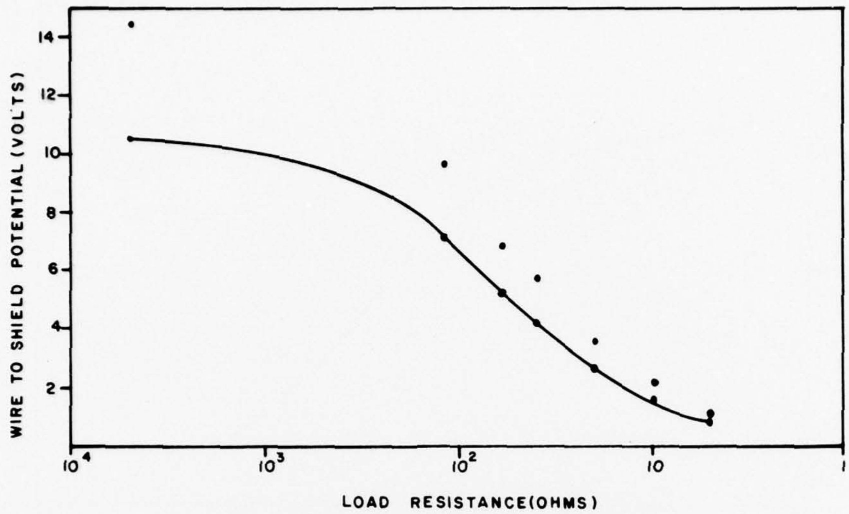

Figure 18. Wire 1 response for 16-wire cable with wires 2 to 5 open-circuit termination and remaining wires short-circuited to shield (experimental ——, theoretical ...).

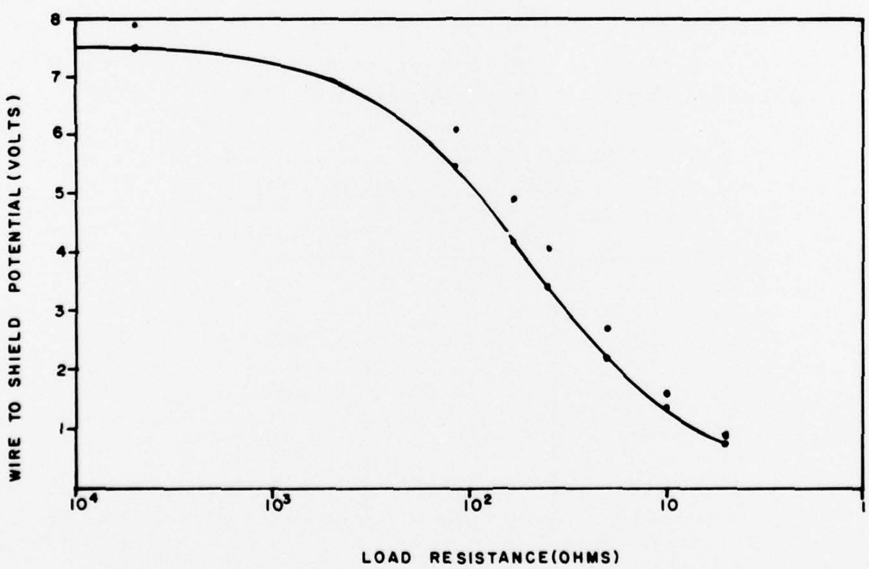

Figure 19. Wire 6 response for 16-wire cable with wires 1 to 5 open-circuit termination and remaining wires short-circuited to shield (experimental ——, theoretical ...).

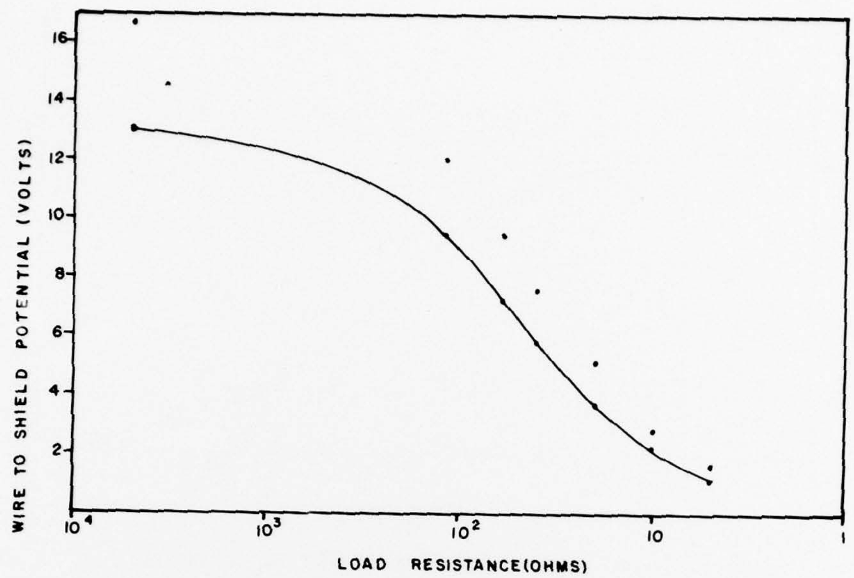

Figure 20. Wire 6 response for 16-wire cable with remaining wires open-circuit termination (experimental ——, theoretical ...).

TABLE VII. SOURCE IMPEDANCE FOR CABLES OF FIGURES 16 TO 20

Figure No.	Source impedance (Ω)	
	Experimental	Theoretical
16	48	38
17	58	51
18	58	60
19	49	41
20	49	48

TABLE VIII. TWO-WIRE CABLE RESPONSE UNDER RESISTIVE END LOADING (FIG. 1a)

Measured conductor pair	Remaining wire loads (Ω)	Drive current $I^+ = \sum_{N=1}^{2} i_N^+$ (A)	Open-circuit voltage (V_{OC}) (V)		Short-circuit current (I_{SX}) (A)		V_{OC}/I_{SX} (Ω)	
			Experi-mental	Theoret-ical	Experi-mental	Theoret-ical	Experi-mental	Theoret-ical
1-S	2-S = 0	1	43	40	0.93	1.0	46	40
1-S	2-S = open	1	48	55	1.0	1.3	48	42

5. SUMMARY

An approach is presented to develop an equivalent circuit compatible with a circuit code for any conductor pair that forms part of a shielded multiwire array. The multiwire shielded cable problem was analyzed as part of the Army MSEP. The theory as reflected by the code of section 3 was compared with the experimental data for four test cables. The theory verification data fall into two groups:

a. Data that test the provisions of the infinitely long cable predictions. These encompass measurements to validate the impedance matrix terms and the I^+ current distribution provisions.

b. Data that test the finite cable end loading interactions. These include the cable response to both reactive and resistive terminations.

The theory is sufficiently developed to allow the preliminary code to be extended to encompass all effects necessary for an EMP assessment program.

6. DISCUSSION

Electromagnetic pulse coupling codes capable of dealing with such omnipresent penetrators as antennas, wires, and cables form an integral part of any comprehensive program of vulnerability assessment and hardening. Because the typical coupling code operates in the frequency domain and any circuit analysis code with which it must interface operates in the time domain, a difficulty arises. The most common solution is to employ the coupling code to develop a Thevenin or Norton equivalent circuit. The resultant complex source impedance can in many cases be translated into a circuit code compatible L-R-C network only with great difficulty, if it can be done at all. Any approach that eliminates the need for developing a source impedance model greatly facilitates the use of such coupling codes. The results presented here on the development of a multiwire shielded cable capability--a capability that can be extended to the single-wire coaxial cable, since it performs all solutions in the time domain--can be used to avoid the source impedance difficulty. Although the approach taken is oriented toward the development of a Thevenin equivalent circuit, the multiwire theory provisions can be readily incorporated into an existing circuit analysis code. Or the development can be extended along the lines indicated in the theory section to build circuit component capability into the multiwire code. The significant difference between interfacing a coaxial cable code like FREFLD with the multiwire code and interfacing it directly with a circuit analysis code (like NET-2) is that the former interface requires only the terminated current component, $I^+(t)$, and the latter requries a current or a voltage source along with a source impedance model.

Although the present development was intended to deal solely with the shield penetration problem, a redefinition of the conditions for establishing the initial, $I^+(t)$, wire current distribution permits a much greater utility of the results. The approach can be readily extended to cover such problem areas as cross talk among conductors and penetration into combinations of shielded and unshielded cabling where the cable bundle coupling can be approximated as a point source rather than as a distributed excitation.

A fundamental problem in applying the code or in attempting to correlate experiment with theory is the poor geometrical stability of many multiwire cables. The four-wire cable (a standard power line with an added external braid) represents as severe an example of this problem as will be typically encountered. The cumulative effect of geometrical instability as the number of wires increased was at the onset uncertain. A comparison of the difference between experiment and theory for the four test cables shows no marked tendency toward a decrease in correlation with increasing wire count. This result is particularly significant since the code is intended to handle cables containing more than 50 wires.

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