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AUTHOR(S): P. Chowdhuri
M. Mahaffy

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scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87545

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WAVE PROPAGATION IN A DC SUPERCONDUCTING CABLE
PART I: ANALYSIS*

P. Chowdhuri, Senior Member, IEEE

M. A. Mahaffy

Los Alamos Scientific Laboratory
Los Alamos, New Mexico 87545

Abstract - We consider a dc superconducting cable design consisting of four concentric metallic cylinders, of which two carry the load current and two comprise the cryogenic enclosure. When a transient voltage is impressed across such a cable, the major dielectric may not be fully stressed to its design value, and unwanted voltage stresses may develop across other parts of the cable. This paper analyzes the surge-voltage propagation characteristics of a four-conductor dc superconducting cable for a step-function input voltage. This analysis, although mainly directed to superconducting cables, is also applicable to other multiconductor tranmission lines. A companion paper discusses the parametric effects of the cable system in optimizing the voltage distribution.

INTRODUCTION

The advantages of transmitting bulk power by a dc superconducting cable has been described previously [1]. However, such a cable must operate reliably under system constraints, e.g., harmonics on the dc, system faults, and transient overvoltages. The behavior of a dc superconducting cable under dc harmonics and system faults has been reported in an earlier paper [2]. This paper discusses the theory of wave propagation in a multiconductor cable system and describes the response of a dc superconducting cable of a specific design to transient voltages. The effects of parametric changes in the system as well as in the cable design, including those of dc conventional cables, are discussed in a companion paper [3].

Figure 1 shows the dc superconducting cable of Los Alamos design. It consists of four concentric cylinders. The innermost cylinder (conductor 1) carries the load current and consists of subcables made up of wires of multifilamentary Nb_3Sn superconductor embedded in copper matrix. The second cylinder (conductor 2), which carries the return current, also consists of copper-stabilized multifilamentary Nb_3Sn superconductor. The cryogenic enclosure is composed of the third and fourth concentric cylinders. The inner cylinder (conductor 3) of the cryogenic enclosure is made of stainless steel and the outer cylinder (conductor 4) of carbon steel. The space between conductors 1 and 2 is filled with

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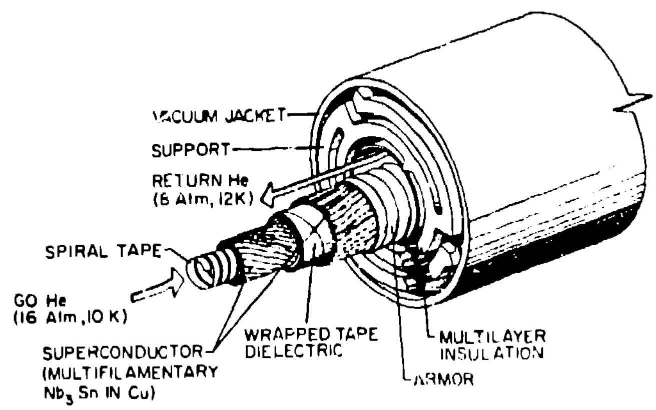

Fig. 1. Conceptual design of a four-conductor dc superconducting cable.

wrapped tape dielectric to withstand the system voltage - steady state dc and transient overvoltages. The space between conductors 2 and 3 is filled with supercritical helium at 1.38 MPa and 12 K. The space between conductors 3 and 4 is evacuated and filled with multilayer thermal insulation. Conductor 4 is isolated from earth by a thin layer of insulation.

When a transient appears on conductor 1, multivelocity voltage waves will propagate along the four conductors and create voltage differences across each pair of conductors, caused by the disparity in the wave velocities that did not exist initially [4]. A flashover or puncture may occur between any pair of conductors if the voltage build-up across the conductor pair exceeds the dielectric strength of the space between them. The weak member of the system may be the evacuated space filled with multilayer thermal insulation within the cryogenic enclosure. Repeated punctures within this space could increase heat leak to the cable, reducing its efficiency.

METHOD OF ANALYSIS

Transient voltages on cable sheaths have been studied previously [5]-[15]. General studies on wave propagation in cables have also been made [16]-[23]. However, in all previous studies, the cable sheath was assumed to be solidly grounded at the terminals, with zero resistance between the sheath and the earth. In practical situations, there is always a finite resistance between the sheath and the earth at the terminals. This grounding resistance may significantly affect the wave propagation in the cable. Although resistivities of the conductors and of the earth have been considered in the analytical models of the previous studies, the sensitivity of these paramaters to the transient performance of the cable has never been explicitly shown.

Because a superconducting cable will be required to transmit high power, its reliability will be of utmost concern. To assure reliability, the distribution of transient voltages amongst its various members should be analyzed under all practical situations. We, therefore, studied the effects of the various parameters (e.g., grounding resistance, conductor and earth resistivities, permittivity of dielectric, etc.) on the transient performance of different designs of cables, with particular emphasis on the superconducing cable.

Rudenburg-Hayashi Model of Transient Impedances

Transient phenomena, such as switching and lightning surges, are usually analyzed using the Laplace transform. Therefore, it is desirable to express the transient impedances in terms of the Laplace-transform operator s.

Rudenberg's analysis [24] of imperfect earth has been extended by Hayashi [25] so that the earth-correction terms can be expressed in terms of the operator s. Rudenberg has represented an underground cable by laying its center conductor on the ground level at the center of a groove of a semicircular shape of radius h from which the earth has been scooped out, h being the distance of the center conductor of the original cable from earth (Fig. 2). The ground impedance as a function of the Laplace-transform operator s can then be expressed as

$$Z_g(s) = \delta_{g1} s^{1/2} - \delta_{g2} + \delta_{g3} s^{-1/2} \ldots \qquad (1)$$

For fast transients, only the first two terms are important, where

$\delta_{g1} = \sqrt{10\, R_g} \times 10^{-4}$
$\delta_{g2} = R_g/4$
$R_g = 2\rho_g/\pi h^2$
ρ_g = soil resistivity, Ω-m
h = distance of center conductor of cable from ground, m

Similarly, the transient impedance of the cable conductor can be expressed as

$$Z_c(s) = \delta_{c1} s^{1/2} + \delta_{c2} + \ldots \qquad (2)$$

where

$\delta_{c1} = \sqrt{10\, R_c} \times 10^{-4}$
$\delta_{c2} = R_c/4$
R_c = dc resistance of the conductor.

For a cable consisting of n concentric cylinders, the earth-correction impedance matrix will then be

$$[\delta] = s^{1/2}[\delta_1] + [\delta_2] \,, \qquad (3)$$

where

$$[\delta_1] = \begin{bmatrix} (\delta_{c11} + \delta_{g11}) & \delta_{g11} & \cdots\cdots & \delta_{g11} \\ \delta_{g11} & & & \\ \vdots & & & \\ \delta_{g11} & \cdots\cdots\cdots\cdots & & (\delta_{c1n} + \delta_{g11}) \end{bmatrix}$$

and

$$[\delta_2] = \begin{bmatrix} (\delta_{c21} - \delta_{g21}) & -\delta_{g21} & \cdots\cdots & -\delta_{g21} \\ -\delta_{g21} & & & \\ \vdots & & & \\ -\delta_{g-1} & \cdots\cdots\cdots\cdots & & (\delta_{c2n} - \delta_{g21}) \end{bmatrix}$$

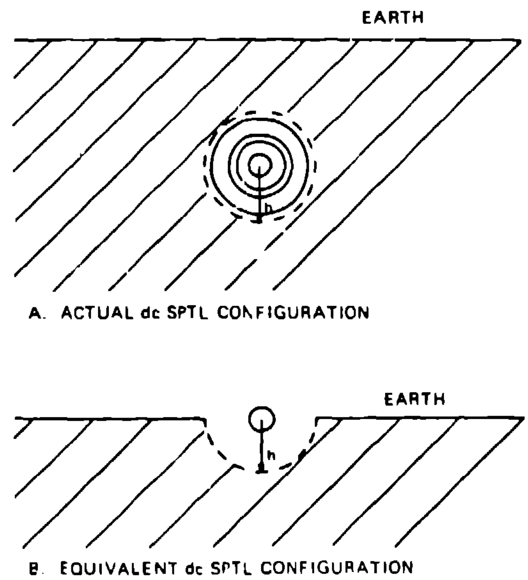

Fig. 2. Rudenberg's model of cable in imperfect earth.

Solution of Transmission-Line Equations

The Laplace transform of the transmission-line voltage equations can be written in matrix form as

$$\begin{aligned} \delta^2[V]/\delta x^2 &= (s^2[L][C] + s^{3/2}[\delta_1][C] + s[\delta_2][C])[\bar{V}] \\ &= [Q]^2[\bar{V}] \end{aligned} \qquad (4)$$

where

$[Q]^2 = (s^2[L][C] + s^{3/2}[\delta_1][C] + s[\delta_2][C]$,

[L] and [C] are the inductance and capacitance matrices of the n-conductor cable, and

$[\delta_1]$ and $[\delta_2]$ are given by (3).

The solution of (4) is given by

$$\begin{aligned} [V] &= \exp(-[Q]x)\,[V_o] \\ &= \left\{\exp(-s[M]^{1/2}x)\exp(-\sqrt{s}[B_1]x/2)\exp(-[B_2]x/2)\right\} \times \\ &\quad [\bar{V}_o] \,, \end{aligned} \qquad (5)$$

where

$[M] = [L][C]$,

$[B_1] = [M]^{1/2}\,[M]^{-1}\,[\delta_1][C]$,

$[B_2] = [M]^{1/2}\,[M]^{-1}\,[\delta_2][C]$,

$[V_o] = [V]$ at $x = 0$.

Each of the three exponential terms needs to be expanded by Sylvester's expansion theorem [25], giving

$$\exp(-s[M]x^{1/2}) = \sum_{r=1}^{n_1} \exp(-sq_{1r}x)\,[a_{1r}] \tag{6}$$

$$\exp(-\sqrt{s}[B_1]x/2) = \sum_{r=1}^{n_2} \exp(-\sqrt{s}q_{2r}x/2)[a_{2r}] \tag{7}$$

$$\exp(-[B_2]x/2) = \sum_{r=1}^{n_3} \exp(-q_{3r}x/2)[a_{3r}] \quad . \tag{8}$$

where

$$[a_{1r}] = \prod_{\substack{p=1,\ldots,n_1 \\ p \neq r}} \left(\frac{q_{1p}^2[U] - [M]}{q_{1p}^2 - q_{1r}^2}\right)^{d_{1p}} ,$$

$$[a_{2r}] = \prod_{\substack{p=1,\ldots,n_2 \\ p \neq r}} \left(\frac{q_{2p}[U] - [M]}{q_{2p} - q_{2r}}\right)^{d_{2p}} ,$$

$$[a_{3r}] = \prod_{\substack{p=1,\ldots,n_3 \\ p \neq r}} \left(\frac{q_{3p}[U] - [M]}{q_{3p} - q_{3r}}\right)^{d_{3p}} .$$

q_{1r}^2 $(r = 1,\ldots,n_1)$ are distinct eigenvalues of $[M]$,
q_{2r} and q_{3r} are distinct eigenvalues of $[B_1]$ and $[B_2]$ respectively,
$[U]$ = identity matrix,
d_{ip} = order of degeneracy of q_{ip} eigenvalue $(i = 1,2,3)$, and
$d_{11}+\ldots+d_{n1} = d_{21}+\ldots+d_{n2} = d_{31}+\ldots+d_{n3} = n$

Boundary Conditions

The length of the cable has been assumed to be semi-infinite in this study; therefore, there would be no reflections from the far end. A voltage V_{01} is injected into conductor 1 at $x=0$, while the other conductors are either grounded through a grounding resistance R_g or left open. In this case, $V_{02}\ldots V_{0n}$ need to be evaluated. These values can be obtained, for known grounding resistance, by solving for the currents at $x=0$.

The Laplace transform of the current matrix is given by

$$[\bar{I}] = -s[C] \int [\bar{V}]dx, \tag{9}$$

where $[\bar{V}]$ is obtained from (5)-(8).

Final Solution

The closed-form solution for the voltage waves, in time domain, is shown in the following equation.

$$[V(t)] = \left\{ \sum_{k=1}^{n_1} [a_{1K}] \sum_{\ell=1}^{n_2} [a_{2\ell}]\,\mathrm{erfc}(q_{2\ell}x/4\sqrt{t-q_{1K}x})\times u(t-q_{1K}x) \right\} \times \left\{ \sum_{m=1}^{n_3} [a_{3m}]\exp(-q_{3m}x/2) \right\} [V_0(t)] \tag{10}$$

where

$u(t-q_{1K}x)$ = delayed step function.

Cable Parameters

Computation of the voltage waves requires that the resistance matrix $[\delta]$, the inductance matrix $[L]$, and the capacitance matrix $[C]$ of the cable be known. As discussed before, the $[\delta]$-matrix was computed by Hayashi's method.

The $[L]$-matrix was evaluated by computing Maxwell's electromagnetic coefficients from the following set of equations,

$$\phi_r = L_{r1}i_1 + \ldots\ldots + L_{rs}i_s + \ldots\ldots + L_{rn}i_n, \tag{11}$$

where

$L_{rs} = L_{sr}$,
ϕ_r = total magnetic flux linking conductor r,
i_r = current flowing through conductor r, and
$r = 1,\ldots\ldots\ldots, n$.

The transient current was assumed to flow along the outer surface of the conductor. The permeability (μ) of a magnetic material was assumed equal to that (μ_0) of free space when a steep-front transient is applied. The coefficients of inductance (L_{rs}) are then given by

$$L_{rs} = (\mu_0/2\pi)\ln(h/r_{so}) \text{ for } r \le s, \text{ H/m}, \tag{12}$$

where

$\mu_0 = 4\pi \times 10^{-7}$ H/m,
h = distance of earth from center of cable, m
r_{so} = outer radius of conductor s, m.

The $[C]$-matrix was evaluated by computing Maxwell's electrostatic coefficients from the following set of equations,

$$Q_r = p_{r1}e_1 + \ldots\ldots + p_{rs}e_s + \ldots\ldots + p_{rn}e_n \tag{13}$$

$$p_{rs} = p_{sr}$$

where

Q_r = electrostatic charge on conductor r,
e_r = potential of conductor r, and
$r = 1, \ldots\ldots, n$.

The coefficients p_{rs} are then given by

$$p_{rn} = \ln(h/r_{no})/2\pi\epsilon_n \text{ for } r \le n \tag{14}$$

$$p_{r(n-1)} = p_{nn} + \ln(r_{ni}/r_{(n-1)o})/2\pi\epsilon_{(n-1)} \text{ for } r \le (n-1)$$

where

ϵ_n = permittivity of conductor n, F/m
r_{ni} = inner radius of conductor n, m
r_{no} = outer radius of conductor n, m

The [C]-matrix is then given by

$$[C] = [p]^{-1} \tag{15}$$

COMPUTATION OF VOLTAGE WAVES

Cable and System Parameters

The conceptual design of the cable is shown in Fig. 1. Table 1 shows the pertinent parameters of the cable. In the analysis, the transient current was assumed to be expelled from the superconductor into the stabilizing copper. The conductors were assumed to be perfect concentric cylinders, and the cable semi-infinite in length.

The step-function voltage wave was applied to conductor 1 at x=0 while each of the other three conductors was connected to earth through a grounding resistance of 10Ω. The earth resistivity was assumed to be 100 Ω-m.

A companion paper shows the effects of various values of grounding resistance, earth resistivity, and cable design parameters on the propagation characteristics of the voltage waves [3].

Computation

A numerical Fortran computer program was developed to solve the voltage equations for a given cable configuration. The voltage waves on each conductor of the cable, as per unit of the applied voltage, are computed at time and distance coordinates specified by the user.

The data put into the program are the number of conductors in the cable, their dc resistances and radii, the dielectric constants of the materials between the conductors, the known initial voltages, the distances between the center of conductors and earth, the earth resistivity, and the terminal resistances between the conductors and earth at x=0.

The code includes a graphics package which plots two-dimensional graphs of the wavefronts at specified distances.

Figure 3 shows the voltage waves on each of the four conductors of the cable at distances of 0.1, 1, and 10 km from the origin.

DISCUSSION

Interpretation of Data

With reference to Fig. 3, the original wave is split into four component waves traveling at unequal velocities. All four component waves are present on conductor 1. The number of component waves decreases progressively from conductor 1 to conductor 4. One single voltage wave of small magnitude travels on conductor 4 (nearest to earth). This component wave which is present on all four conductors at x=0 is highly attenuated within a short distance from the origin. This wave is not discernable in the figures.

TABLE I

Parameters of 100-kV dc Superconducting Cable

Outer radius of conductor 1,	r_{1o} = 22.7 mm
DC resistance of conductor 1,	R_{c1} = 0.2 μΩ/m
Inner radius of conductor 2,	r_{2i} = 28.3 mm
Outer radius of conductor 2,	r_{2o} = 35.0 mm
DC resistance of conductor 2,	R_{c2} = 0.2 μΩ/m
Inner radius of conductor 3,	r_{3i} = 45.0 mm
Outer radius of conductor 3,	r_{3o} = 49.0 mm
DC resistance of conductor 3,	R_{c3} = 440.0 μΩ/m
Inner radius of conductor 4,	r_{4i} = 90.0 mm
Outer radius of conductor 4,	r_{4o} = 94.0 mm
DC resistance of conductor 4,	R_{c4} = 43.0 μΩ/m
Distance of cable center to earth	h = 98.0 mm
Dielectric constants:	k_1 = 2.2
	k_2 = 1.0
	k_3 = 1.0
	k_4 = 3.0

The voltage between each conductor and ground changes abruptly as the component voltage waves arrive at a point along the cable at different times. For instance, conductor 1 experiences abrupt voltage changes at 3.45, 3.86, 5.77 and 6.93 μs as the four component waves arrive at x = 1 km (Fig. 3b). Similarly, three component waves arrive on conductor 2 at 3.45, 3.86, and 5.77 μs; two component waves on conductor 3 at 3.45 and 3.86 μs; and, one single wave on conductor 4 at 5.77 μs. The component wave (of small magnitude) which arrives at x = 1 km on all four conductors at 5.77 μs is highly attenuated within a short distance from the origin. This wave is not discernible in the figures.

The primary voltage wave on conductor 3 (stainless steel) attenuates significantly with time. With increase in distance along the cable, the peak value of this wave increases, although the attenuation rate with time increases also. In general, the front time of the component waves increases with distance along the cable.

The voltage difference between each pair of conductors can also be ascertained from Fig. 3. At x = 1 km (Fig. 3b), no voltage difference appears between conductors 1, 2, and 3 until the second wave arrives on conductors 1 and 2 at 3.86 μs. Conductors 1 and 2 remain at equal voltages until the fourth wave arrives on conductor 1 at 6.93 μs, when about 0.65 p.u. is developed across conductors 1 and 2. The voltage spike developed across the cryogenic enclosure (between conductors 3 and 4) at x = 1 km is about 0.20 p.u. For a 100-kV cable (BIL = 250 kV), 50 kV of transient voltage will thus be impressed across the cryogenic enclosure. About 0.24 p.u. (i.e., 59.5 kV) will be impressed across the helium space between conductors 2 and 3. The major dielectric (between conductors 1 and 2) will carry only 0.65 p.u. (i.e., 162.5 kV).

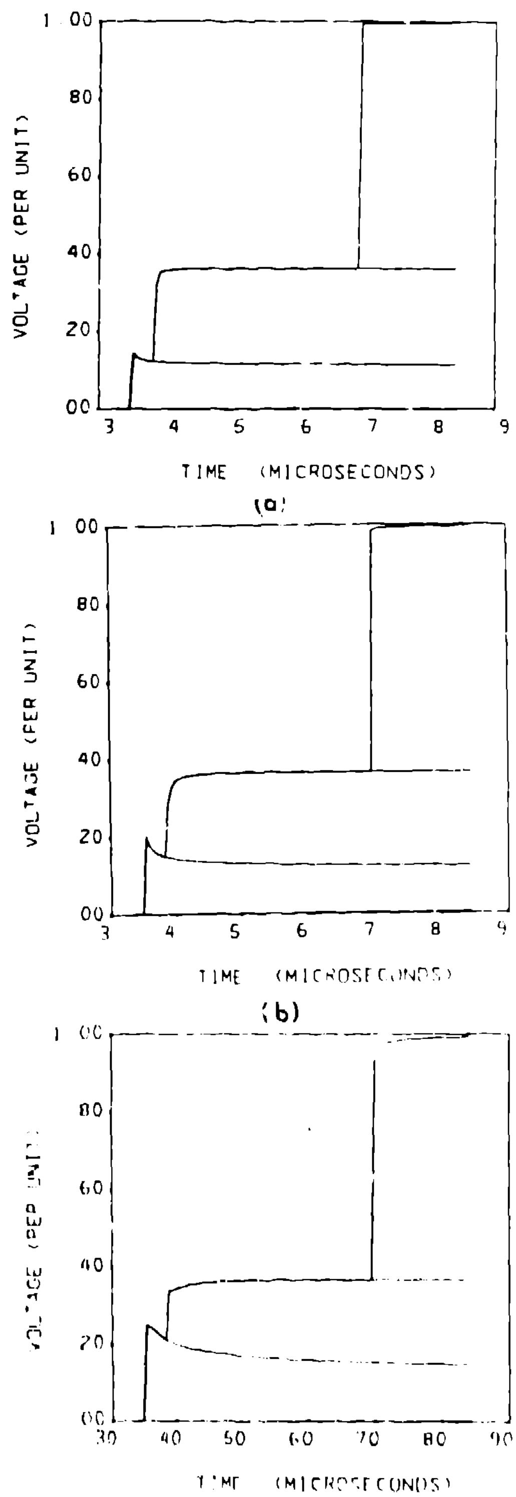

Fig. 3. Step response of a semi-infinite 100-kV four-conductor dc superconducting cable. R_g = 10Ω at x=0; ρ_g = 100 Ω-m (a) x = 100 m; (b) x = 1 km; (c) x = 10 km. Four, three, two and one component waves travel along conductors 1, 2, 3, and 4, respectively. The component wave which is present on all four conductors is highly attenuated and is not discernible in the figures.

The voltage stress across the cryogenic enclosure can be relieved by reducing the BIL (hence the steady-state voltage rating) of the cable. Other alternative solutions such as metallic shorts across the enclosure at regular intervals and design optimization in the cable and system can also reduce this voltage stress. P[illegible]metric changes in the cable and system are discuss[illegible] the companion paper [3].

Limitations of the Analysis

The δ-matrices were evaluated by considering only the first two terms of (1) and (2) in order to keep the analysis simple and manageable. As a consequence, this analysis is valid at the wave-front of transients. To provide definition to the valid time duration, extensive computations were carried out by comparing results from the first terms of (1) and (2), with those from the first two terms.

It was found that one of the eigenvalues (q_{3m}) of the B_2-matrix in (8) was negative. This will increase the corresponding exponential term in (10) with increase in distance along the cable. It was also found that all but one resultant matrix, $[a_{1k}] \times [a_{2\ell}] \times [a_{3m}]$, which is multiplied by this exponential term, is null. It was essential that this particular matrix is non-zero so that the initial conditions at x=0 are consistent. This term was evaluated by using the exponential equivalent of erfc(y) for large values of y, i.e.,

$$\mathrm{erfc}(y) \approx \exp(-y^2)/y\sqrt{\pi} \tag{16}$$

where

$$y = q_{2\ell}x/4\sqrt{t-q_{1k}x}.$$

The time limit was set such that $y^2 \geq q_{3m}x/2$. By simplifying the algebra, one gets

$$(t-t_{1k}) \leq q_{2\ell}^2/8q_{3m}, \tag{17}$$

where

t = time limit
t_{1k} = $1/q_{1k}$, and
q_{1k}, $q_{2\ell}$ and q_{3m} are the eigenvalues corresponding to the non-zero matrix $[a_{1k}] \times [a_{2\ell}] \times [a_{3m}]$.

More terms of (1) and (2) should be included if computation at longer times is desired. As the front time is of concern in most applications, inclusion of just the first two terms of (1) and (2) should be sufficient, considering the elegance, simplicity, and economy in computation time of the method described.

CONCLUSIONS

1. The step response of a dc superconducting cable to transient voltages has been described using the Laplace transformation technique, taking into account the transient impedances of the cable conductors and earth.

2. Transient voltages will not stress the major dielectric of the cable system to its full BIL capability.

3. Surge protection, cable design optimization, and system coordination will be required to limit transient voltages across the cryogenic enclosure of the cable.

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Pritindra Chowdhuri (M'52-SM'60) received B.Sc. in physics and M.Sc. in applied physics from the Calcutta University, M.S. in electrical engineering from the Illinois Institute of Technology, and D. Eng. in engineering science from the Rensselaer Polytechnic Institute in 1945, 1948, 1951, and 1966 respectively.

He has worked with the Lightning Arresters Design Section of the Westinghouse

Electric Corporation, East Pittsburgh, PA, High-Voltage Laboratories of the Maschinenfabrik Oerlikon, Zurich, Switzerland, and of the High Voltage Research Commission (FKH), Daeniken, Switzerland. He joined the General Electric Company in 1956, where he had various assignments, at the High-Voltage Laboratory, Pittsfield, MA, the General Engineering Laboratory, Schenectady, NY, and the Materials & Processes Laboratory, Erie, PA. At present, he is a Staff Member with the Los Alamos Scientific Laboratory, Los Alamos NM.

Dr. Chowdhuri is a Fellow of the Institution of Electrical Engineers, England, the American Association for the Advancement of Science and the New York Academy of Sciences. He is a member of the Power Engineering Society, Industry Applications Society, Electromagnetic Compatibility Society, Electrical Insulation Society of the IEEE, and of CIGRE. He has received four U.S. patents.

Mary-Anne Mahaffy was bron in Torrance, CA, on November 17, 1947. She received the B.S. degree in physics from Antioch College, Yellow Springs, and the M.S. degree in geology from University of Colorado, Boulder, in 1969, and 1974 respectively.

From 1974 to 1976, she was a research consultant for INSTAAR and CIRES, University of Colorado, Boulder, working in ice sheet models. In 1978, she joined the Los Alamos Scientific Laboratory, Los Alamos, NM, and is now a staff member in the computer division.