

TRANSIENT HEAT TRANSFER FROM BURIED
ELECTRICAL CABLES UNDER SHORT-CIRCUIT CONDITIONS

A THESIS

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ELECTRICAL CABLES UNDER SHORT-CIRCUIT CONDITIONS

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NOMENCLATURE

Symbol	Definition	Units
C	Specific heat	watt-sec/gm°C
C_1 --- C_{10}	Constant	dimensionless
D_s	Diameter of wire shield	cm
D_c	Diameter of conductor	cm
D_e	Diameter of start of the earth portion of the thermal circuit	cm
D_I	Dielectric loss in insulator	watt/cm
D_x	Fictitious diameter at which the effect of loss factor commences	cm
F	Product of ratios of distances	dimensionless
F(x)	Derived Bessel function of x (Table 3)	
Fo	Fourier number	dimensionless
H	Dimensionless heat generation	dimensionless
I	Current (RMS)	amps
k	Thermal conductivity	watt/cm°C
K_s	Skin effect correction factor for annular and segmented conductor	dimensionless
L	Depth of reference cable below earth surface	cm
lf	Load factor	dimensionless
LF	loss factor	dimensionless

Symbol	Definition	Units
M	Number of nodes for each material	dimensionless
N_s	Number of wires in the shield	dimensionless
N	Number of conductors within a stated diameter	dimensionless
P	Percent area of shield wire in contact with insulation	dimensionless
$\cos \phi$	Power factor of insulator	dimensionless
q'''	Heat generation per unit volume	watts/cm ³
q_s	Ratio of the sum of the losses in the conductor and shields to the losses in the conductor	dimensionless
q_e	Ratio of the sum of the losses in the conductors, sheath and conduit to the losses in the conductor	dimensionless
r	Radius	cm
R	Electrical resistance	ohms
R_{ac}	Total ac resistance per conductor	ohms
R_{dc}	Total dc resistance of conductor	ohms
R_s	dc resistance of shield	ohms
\hat{R}	Thermal resistance	thermal ohm-cm
\hat{R}_a	Thermal resistance of air	thermal ohm-cm
\hat{R}_i	Thermal resistance of insulation	thermal ohm-cm
\hat{R}_e	Thermal resistance between conduit and ambient	thermal ohm-cm

Symbol	Definition	Units
\hat{R}_e	Effective thermal resistance between diameter D_e and ambient earth including the effects of loss factor and mutual heating by other cables	thermal ohm-cm
\hat{R}_s	Thermal resistance of wire shield	thermal ohm-cm
t	Time	sec
t_s	Transient time	sec
T	Temperature	$^{\circ}\text{C}$
ΔT_c	Temperature rise of conductor due to current produced losses	$^{\circ}\text{C}$
ΔT_d	Temperature rise of conductor due to dielectric loss	$^{\circ}\text{C}$
W_c	Losses developed in the conductor	watt/cm
Y_c	The increment of ac/dc ratio due to losses originating in the conductor	dimensionless
ρ	Density of material	gm/cc
ρ_e	Electrical resistivity	ohm-cm
ξ	Dimensionless radius	dimensionless
θ	Dimensionless temperature	dimensionless
τ	Dimensionless time	dimensionless
α	Thermal diffusivity	cm^2/sec

Subscripts:

C	Conductor	J	Jacket
I	Insulator	E	Earth
S	Shield or Sheath		

SUMMARY

This thesis describes an analytical technique and computer program which calculates the steady state and transient temperature distribution in underground electrical power cables. The transient conditions are assumed to be caused by short-circuit conditions which result in several circuit breaker reclosure cycles. The analysis is the result of an energy balance which includes the cable and surrounding earth. The general partial differential equations for the local transient temperatures are too difficult to solve in a closed form, so an implicit numerical technique was used to solve the resulting system of finite difference equations. The necessary electrical considerations such as dielectric loss, skin effect, circulating shield currents and effective soil thermal resistance are described in Section II of the thesis. These factors are integrated into the general energy balance.

The program predicts the radial temperature distribution as a function of time in the four cable materials and the earth. The initial cable temperature distribution is assumed to be the steady state values which exist when the cable is operated without current fluctuations.

The resulting computer program is a design tool which can be used to predict possible cable geometries and operating conditions which will lead to safe material temperatures under steady state and transient conditions. The program is organized so that a person responsible for cable design or operation can easily determine the effect that changes in cable geometry and properties can have on the cable temperatures.

Program results have been compared with other data which exist in the open literature, but results for transient conditions are extremely scarce. When comparisons can be made, the results of the computer program compare favorably. For the steady state cases checked, the program predicts steady conductor temperatures which are within 8°C of the values listed in the IPCEA-NEMA ampacity tables. The transient results are also within about 15°C of the experimental results obtained by Georgia Power Company and the theoretical results of Mildner [17].

A section of the thesis describes the contents of the computer program and the operation of the program so that results can be obtained by a user who has a minimum of programming knowledge. An attempt has been made to keep the program general so that it will apply to as many different practical cable designs as possible. The program consists of a main program, a data set and twelve subprograms. The program language is Extended FORTRAN IV.

CHAPTER I

INTRODUCTION

A. Description Of Problem

Presently the majority of electrical current at transmission and distribution voltages is transported on overhead conductors supported by poles or metal towers. The heat generated in the conductor due to I^2R losses is dissipated into the air and overheating of the cable is rarely a problem. The current trend in power industry is to replace overhead cables with underground cables, and each year more cable, particularly distribution cable, is placed underground. This trend is accelerated by pressure from environmental and ecology groups who object to power poles and overhead cables in residential areas. The trend in the industry is, therefore, toward underground distribution systems and to a lesser extent to underground transmission systems.

One problem encountered in an underground system which is not a serious problem for overhead conditions is the effective dissipation of heat so as to prevent the cable insulation from melting. Since soil is a particularly good insulator, the problem is an acute one. Unfortunately, the transfer of heat through a power cable into the surrounding soil is a complex one. The heat is not only generated in the conductor but it also may be generated in the insulator and the metallic shield material. The problem is further complicated by the fact that several cables are usually buried near each other and therefore mutual heating effects must

be accounted for. The symmetry that is desirable in an analytical model is therefore not provided in practice and mutual heating between cables must be taken into account.

One of the primary objectives of this thesis is to provide information on the steady state temperature distribution in an underground cable for a given set of parameters such as cable geometry, thermal properties and electrical properties. An analysis of this type using heat transfer principles would provide valuable information because it would allow decisions to be made on the upper current limits for each cable system. Cables could then be permitted to carry the maximum current under emergency conditions with relative assurance that they would not be damaged by excessive temperatures.

The type of information generated by such a project can have a tremendous economic impact. It is estimated that power losses in transmission and distribution systems exceed \$2 billion in lost revenue annually in the United States [14]. The potential for savings and the incentive to work in the area of heat losses from cables is considerable. Any information which could lead to an increase in cable ampacity without damage to the cable could easily recover the funds spent on the research.

Another significant problem associated with underground cable is the dissipation of heat during short time transients. Usually these transients are due to a short-circuit in the system which causes a brief surge in the current level. The system is often protected by circuit breakers which automatically detect the presence of the short and open the circuit. The breaker will continue to sequence through several open and closed cycles assuming that the reason for the short circuit will be

corrected because many underground circuits exit to overhead lines. During a short-circuit condition, the currents through the shield and conductor are often an order of magnitude higher than the level carried during normal operation. The sudden increase in current produces a large temperature rise, particularly near the shield material.

The second major objective of this thesis is to predict the temperature distribution in the cable under typical short-circuit conditions. Results from this portion of the project will predict those factors which will limit cable temperature to safe values.

The heat transfer analysis used to predict steady state, and particularly the short-circuit transient temperature distribution in the underground cable system is quite involved. The transient portion involves the solution of five nonhomogeneous partial differential equations with variable coefficients. Due to this complexity a digital computer program was written to simulate the problem and a numerical technique was used to solve for the temperature distribution. The predicted results are compared with existing published data, although temperature values either theoretical or experimental which exist under transient conditions are very scarce.

The results are analyzed to show the effect of the various input parameters on the cable temperature distribution. Hopefully, the results will suggest changes in either cable design or the manner in which the cable can be buried so that the effect of internal heat generation and the amount of lost generated revenue is minimized.

B. Literature Search

There are several papers which discuss the energy losses and the temperature rise in the electrical cables.

D. M. Simmons [1] discussed the fundamental constants involved in electric circuits. The problem of determining the current carrying capacity as limited by temperature rise is then discussed. The paper by Simmons is the first extensive work to treat the problem of heat transfer from power cables.

Neher and McGrath [2] accounted for recent practices in the power industry and have applied their results to account for load cycling of the cable and temperature rise due to the presence of duct structures which are now frequently used in underground cable systems. The analysis presented in this paper deals primarily with steady state conditions although one highly simplified equation is given for the determination of temperatures during emergency ratings. The results of Neher and McGrath are used extensively in this thesis.

J. V. Schmill [15] established equations which determine the effective thermal resistivity of soils when moisture migration occurs and when steady state condition has been reached.

J. H. Neher [8] has calculated the transient temperature rise of a buried cable system. The calculations assume there is no temperature rise in the earth and it also introduces a suitable formulation for the effective earth transient.

B. M. Weedy [6] has used a numerical method to predict the transient temperature rise in single core cables resulting from short-circuit considerations. The results indicate that for paper/oil cables, thermal

instability initiated by faults is unlikely to be experienced in practice.

Georgia Poer Company [4] has conducted several thermal tests on extruded dielectric underground cables. The tests involve the direct monitoring of the temperature rise in the shield of a three cable system. The results of these tests are compared with the analytical results of the transient program.

M. A. Martin and R. G. Lukac [3] have determined the faults current capacity of various type metallic shields by means of a laboratory test. M. A. Martin and A. W. Reczek [4] have written a paper that shows the temperature rise resulting from numerous short circuit tests with multiple circuit breaker reclosures. The tests were conducted on short lengths of round wire shielded extruded dielectric power cables and the transient temperature rise of the metallic shield was measured with thermocouples.

CHAPTER II

THEORY

A. General Considerations

The cross section of a typical type of extruded dielectric power cable frequently used in electrical distribution systems is shown in Figure 1 and Figure 2. The cable consists of a conductor composed of stranded wires. The usual conductor material is aluminum, although copper is sometimes used. The conductor is surrounded by a cross-linked polyethylene (XLP) insulation. A wire or solid metallic shield is placed over the insulation. The shield wires are covered with a dielectric jacket material which is often a polyvinylchloride (PVC) or high molecular weight polyethylene (HWM).

B. Heat Transfer Considerations

The analysis used to determine the local temperature distribution in the cable shown in Figure 1 and Figure 2 is limited by several assumptions that were made at the beginning of the project. These assumptions are:

1. The temperature distribution is assumed to be a function of only time and the radial coordinate, that is $T = T(r, t)$. This assumption is justified because the ratio of cable length to diameter is extremely large.
2. The cables are directly buried underground. Cable ducts are not considered in this analysis.

3. The thermal properties and density (C_p , ρ , k) of the cable materials and earth are constant.
4. Frequency of the current in the cables is 60 Hz.
5. Only single, solid stranded conductors are considered.
6. The shield material is assumed to be copper, but the conductor material can be either copper or aluminum.
7. The spacing between the cables is equal.

The cable temperature can be determined by applying an energy balance to the five materials which make up the composite cable. These materials are the conductor, insulation, shield, jacket and earth. The applicable energy equation written in cylindrical coordinates simplified for the above eight assumption is:

$$\rho c \frac{\partial T}{\partial t} = \frac{k}{r} \frac{\partial}{\partial r} \left(\frac{1}{r} \frac{\partial T}{\partial r} \right) + q''' \quad (\text{II.B.1})$$

where q''' is the rate of heat generated inside the cable material per unit volume.

There is no heat generated in the earth or jacket material because no current flows through these two materials. However, current through the conductor causes heat to be generated in the metallic conductor. Furthermore, circulating currents through the shield cause heat generation in the shield material. Also due to the relatively high voltages experienced in underground distribution cables, a small amount of current leaks from the main conductor to the shield wires causing heat generation

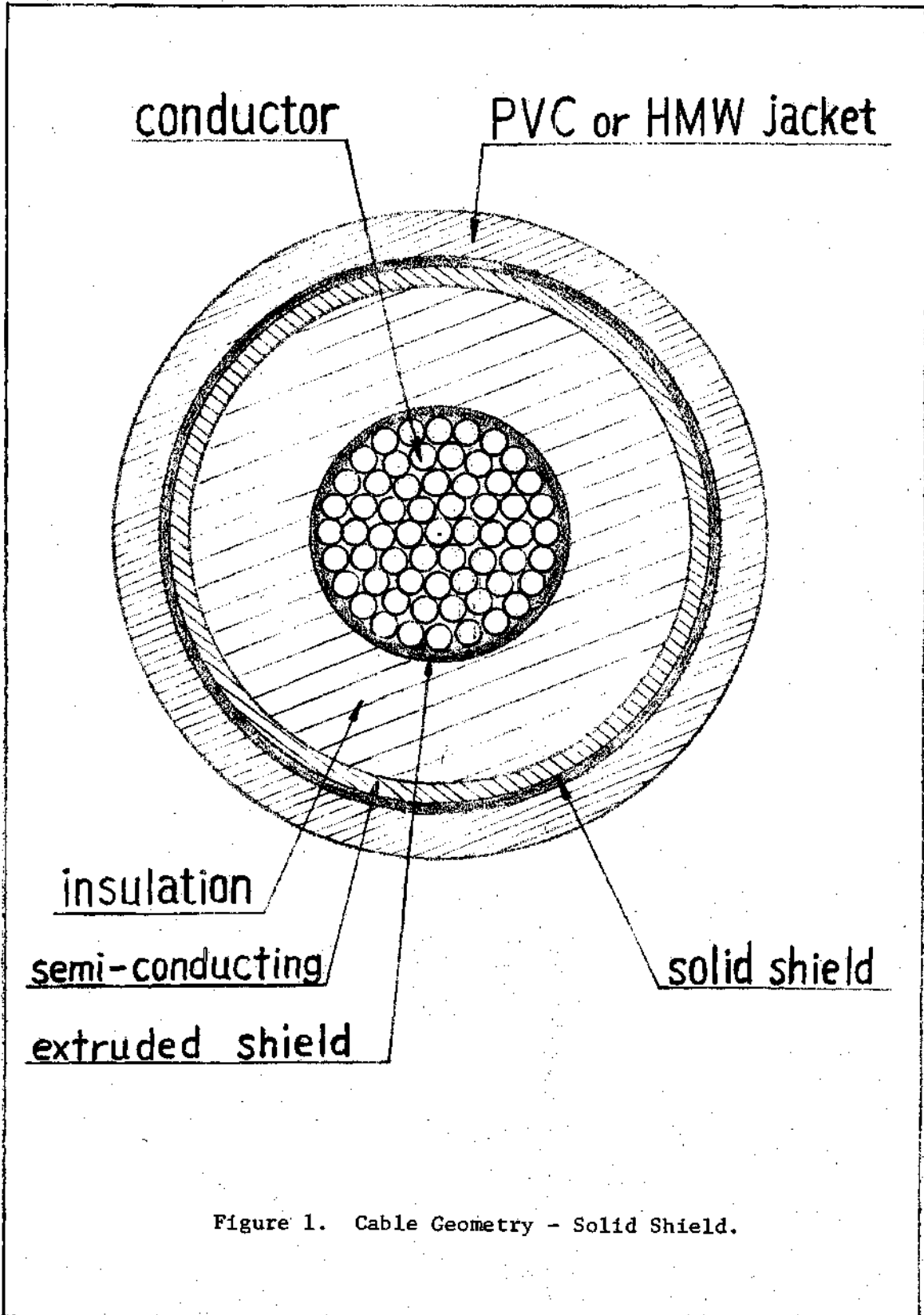


Figure 1. Cable Geometry - Solid Shield.

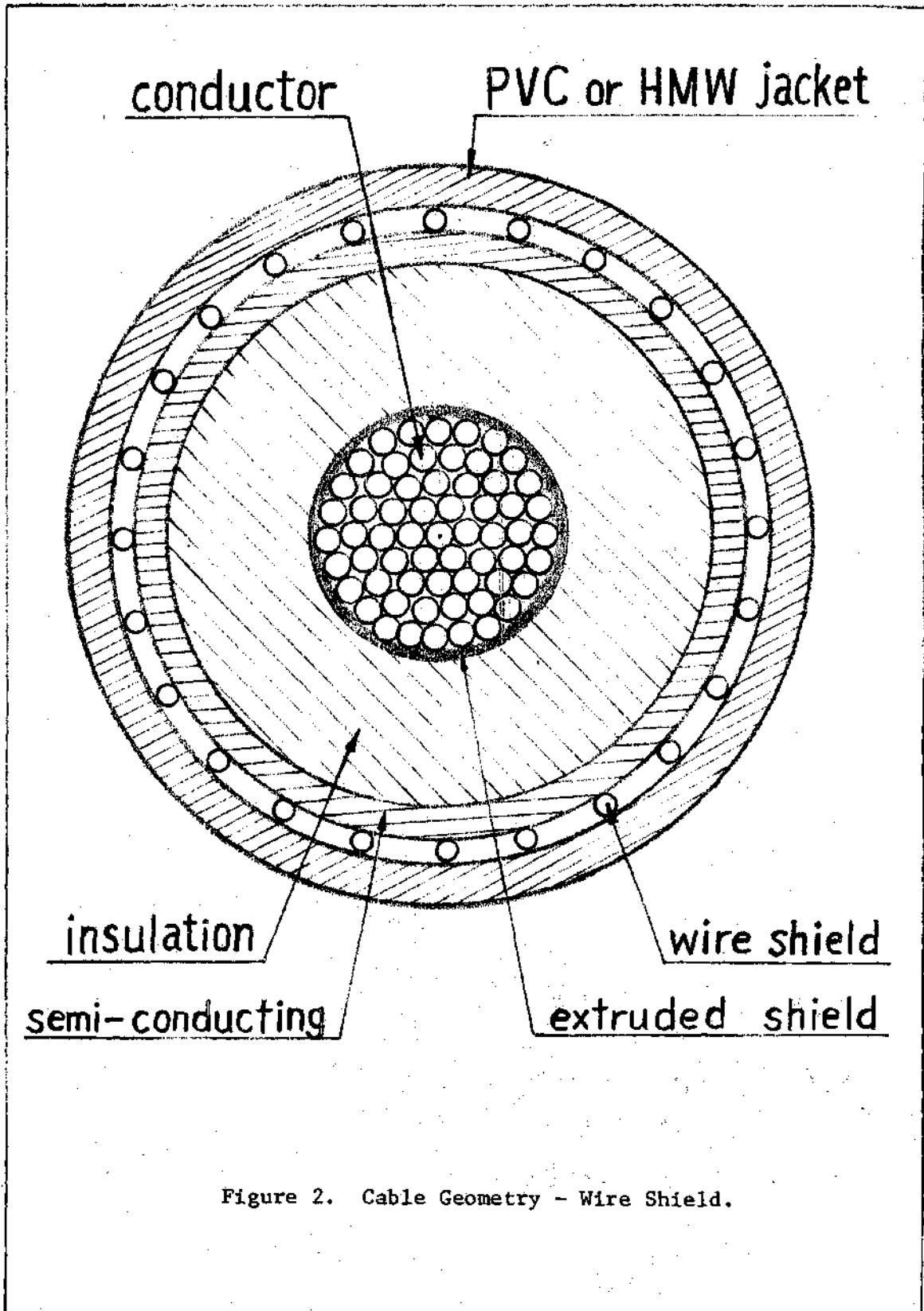


Figure 2. Cable Geometry - Wire Shield.

in the insulation. This heat generation is usually referred to as a dielectric loss.

The heat generated per unit volume in the conductor and shield is of the form:

$$q''' = \frac{I^2 R}{V} \quad (\text{II.B.2})$$

where I = current in the conductor or shield or insulator

R = electrical resistance of the material

V = volume.

The electrical resistance R can be expressed in terms of the electrical resistivity ρ_e , of the material (Table 1) on

$$R = \frac{\rho_e L}{A} \quad (\text{II.B.3})$$

where A = cross sectional area of the conductor

L = length of conductor.

Therefore, in terms of the geometry of Figure 1 and Figure 2, the heat source for the conductor is

Table 1. Electrical Resistivity Of
Various Materials (From Reference 2)

Material	ρ_e (circular mil) ohms per foot at 20°C	C
Copper (100% IACS)	10.371	234.5
Aluminum (61% IACS)	17.002	228.1
Commercial Bronze (43.6% IACS)	23.8	564

$$q_c''' = \rho_e \left(\frac{I_c}{A_c} \right)^2$$

and for the shield is

$$q_s''' = \rho_e \left(\frac{I_s}{A_s} \right)^2$$

For a solid shield the cross sectional area is

$$A_s = (r_s^2 - r_I^2)$$

and for a wire shield A_s is

$$A_s = N_s \frac{\pi d_s^2}{4}$$

where N_s = number of shield wires

d_s = diameter of shield wires.

The heat generation in the insulator given by the dielectric loss in the insulator

$$q_I''' = \frac{D_I}{A_I}$$

The dielectric loss per unit length will be expressed in terms of basic electrical properties in section II.

The analysis assumes that the temperature distribution is a function of only time and radius. Therefore, any cable layer which has a variation in material properties with circumferencial angle must be replaced by a material which has properties that are uniform with angle. The only cable material which has property variations with angle is the shield when it is composed of wires.

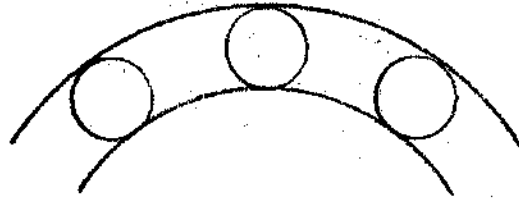
The effective thermal conductivity of the solid shield is simply equal to the actual conductivity when the shield is solid. When the shield is composed of wires, the effective thermal conductivity k_{eq} depends upon the amount of jacket and shield material which actually contacts each shield wire. When the cable is relatively new, the contact between the shield wire and jacket is practically along one line. But after the cable has aged and the shield wire has been heated, the jacket material begins to surround the wire and the contact becomes more over an entire segment of the wire (see Figure 3).

The effective thermal conductivity becomes a function of the percent of area contact between the shield wire and adjacent insulations. For heat flow through a parallel circuit composed of shield wires surrounded by air the thermal resistance is

$$\frac{1}{R_{eq}} = \frac{1}{R_a} + \frac{1}{R_s}$$

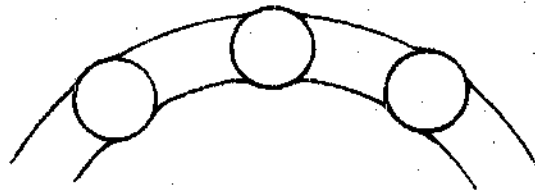
The thermal resistance of a hollow cylinder of material with an equivalent thermal conductivity R_{eq} , is

a.



Line contact for new cable.

b.



Area contact for cable which has been in service.

Figure 3. Variation Of Contact Between
Shield Wire And Insulation.

$$R_{eq} = \frac{\ln(r_s/r_I)}{2 k_{eq} L}$$

Using these two expressions, the equivalent thermal conductivity of the shield becomes (see Appendix A for details of derivation)

$$K_{eq} = \frac{N_s}{2} \left[k_s \frac{\pi P D_s}{2r_I} + k_A \frac{\left(2\pi - N_s \frac{D_s P \pi}{2r_I} \right)}{N_s} \right]$$

where N_s = the number of wire shield

d = the diameter of wire shield

P = the percent area of contact

r_I = the radius of insulation

k_s = the thermal conductivity of copper

k_A = the thermal conductivity of air

The equivalent density and specific heat of the shield layer must also be evaluated when the shield consists of wires. However, very little accuracy is lost by assuming the equivalent properties are those of copper alone. This assumption is particularly valid because the energy generated in the shield wire has very little time during a short circuit to be conducted into the surrounding air. As a result, the effective density and specific heat of the shield is used only when the short-circuit has been open. The shield temperature which results from this assumption can be considered to be the maximum value which will occur at the point where the wire contacts the jacket material. The jacket temperature adjacent to the

air gap will be somewhat higher.

The differential equation (II.B.1) was non-dimensionalized by defining the following new parameters:

$$\xi = \frac{r}{r_m}$$

$$\theta = \frac{T - T_\infty}{T_\infty}$$

$$\tau = \frac{t}{t_s}$$

where r_m = the outside radius of individual material

T_∞ = the temperature of earth where $r \rightarrow \infty$

t_s = transient time.

Introducing these dimensionless groups into equation (II.B.1) results in a dimensionless energy equation applicable to all five materials of the form.

$$\frac{1}{\xi} \frac{\partial}{\partial \xi} \left(\xi \frac{\partial \theta}{\partial \xi} \right) + \frac{r^2}{kT_\infty} q''' = \frac{r^2 \rho c}{t_s k} \left(\frac{\partial \theta}{\partial \tau} \right) \quad (\text{II.B.4})$$

The terms

$$\frac{r^2 q'''}{kT_\infty} = H$$

and

$$\frac{r^2 \rho C}{t_s k} = \frac{1}{F_o}$$

are both dimensionless. The first one represents the heat generated in each material and it will be called the heat source, H. The second term is the reciprocal of the familiar Fourier number that occurs in transient conduction problems.

Equation (II.B.4) now becomes

$$\frac{1}{\xi} \frac{\partial}{\partial \xi} \left(\xi \frac{\partial \theta}{\partial \xi} \right) + H = \frac{1}{F_o} \left(\frac{\partial \theta}{\partial \tau} \right) \quad (\text{II.B.5})$$

This dimensionless equation is actually the conservation of energy equation and it applies to each of the five materials which made up the composite cable. The equation for each material becomes:

Conductor (subscript c)

$$\frac{1}{\xi_c} \frac{\partial}{\partial \xi_c} \left(\xi_c \frac{\partial \theta_c}{\partial \xi_c} \right) + H_c = \frac{1}{F_{oc}} \left(\frac{\partial \theta_c}{\partial \tau} \right) \quad (\text{II.B.6})$$

$$\text{where } H_c = \rho_{ec} \left(\frac{I_c}{A_c} \right)^2 \frac{r_c^2}{k_c T_\infty} \quad \frac{1}{F_{oc}} = \frac{r_c^2 \rho_c C_c}{t_s k_c}$$

Insulator (subscript I)

$$\frac{1}{\xi_I} \frac{\partial}{\partial \xi_I} \left(\xi_I \frac{\partial \theta_I}{\partial \xi_I} \right) + H_I = \frac{1}{F_{OI}} \left(\frac{\partial \theta_I}{\partial \tau} \right) \quad (\text{II.B.7})$$

$$\text{where } H_I = \frac{D_I}{A_I} \times \frac{r_I^2}{k_I T_\infty} \quad \frac{1}{F_{OI}} = \frac{r_I^2 \rho_I C_I}{t_s k_I}$$

Shield (subscript s)

$$\frac{1}{\xi_s} \frac{\partial}{\partial \xi_s} \left(\xi_s \frac{\partial \theta_s}{\partial \xi_s} \right) + H_s = \frac{1}{F_{OS}} \left(\frac{\partial \theta_s}{\partial \tau} \right) \quad (\text{II.B.8})$$

$$\text{where } H_s = \rho_{es} \left(\frac{r_s}{A_s} \right)^2 \frac{r_s^2}{k_s T_\infty} \quad \frac{1}{F_{OS}} = \frac{r_s^2 \rho_s C_s}{t_s k_s}$$

Jacket (subscript J)

$$\frac{1}{\xi_J} \frac{\partial}{\partial \xi_J} \left(\xi_J \frac{\partial \theta_J}{\partial \xi_J} \right) = \frac{1}{F_{OJ}} \left(\frac{\partial \theta_J}{\partial \tau} \right) \quad (\text{II.B.9})$$

$$\text{where } \frac{1}{F_{OJ}} = \frac{r_J^2 \rho_J C_J}{t_s k_s}$$

Earth (subscript E)

$$\frac{1}{\xi_E} \frac{\partial}{\partial \xi_E} \left(\xi_E \frac{\partial \theta_E}{\partial \xi_E} \right) = \frac{1}{F_{OE}} \left(\frac{\partial \theta_E}{\partial \tau} \right) \quad (\text{II.B.10})$$

$$\text{where } \frac{1}{F_{OE}} = \frac{r_E^2 \rho_E C_E}{t_s k_E}$$

The energy equation is second order in r and therefore two boundary conditions for each are necessary. The two boundary conditions are based on the continuity of temperature and heat flux at each interface between the materials which make up the cable. Continuity of heat flux and temperature requires:

1. At interface between the conductor and insulator

$$\left[k_c \frac{\theta_c}{\xi_c} \Big|_{\xi_c} = 1 \right] = \left[k_I \frac{\theta_I}{\xi_I} \Big|_{\xi} = \frac{r_c}{r_I} \right] \quad (\text{II.B.11})$$

$$\left[\theta_c \Big|_{\xi_c} = 1 \right] = \left[\theta_I \Big|_{\xi_I} = \frac{r_c}{r_I} \right]$$

2. At interface between the insulator and shield

$$\left[k_I \frac{\partial \theta_I}{\partial \xi_I} \Big|_{\xi_I} = 1 \right] = \left[k_s \frac{\partial \theta_s}{\partial \xi_s} \Big|_{\xi_s} = \frac{r_I}{r_s} \right] \quad (\text{II.B.12})$$

$$\left[\theta_I \Big|_{\xi_I = 1} \right] = \left[\theta_S \Big|_{\xi_S = \frac{r_I}{r_S}} \right]$$

3. At interface between the shield and jacket

$$\left[k_S \frac{\partial \theta_S}{\partial \xi_S} \Big|_{\xi_S = 1} \right] = \left[k_J \frac{\partial \theta_J}{\partial \xi_J} \Big|_{\xi_J = \frac{r_S}{r_J}} \right] \quad (\text{II.B.13})$$

$$\left[\theta_S \Big|_{\xi_S = 1} \right] = \left[\theta_J \Big|_{\xi_J = \frac{r_S}{r_J}} \right]$$

4. At interface between the jacket and earth

$$\left[k_J \frac{\partial \theta_J}{\partial \xi_J} \Big|_{\xi_J = 1} \right] = \left[k_E \frac{\partial \theta_E}{\partial \xi_E} \Big|_{\xi_E = \frac{r_J}{r_E}} \right] \quad (\text{II.B.14})$$

$$\left[\theta_J \Big|_{\xi_J = 1} \right] = \left[\theta_E \Big|_{\xi_E = \frac{r_J}{r_E}} \right]$$

The last two boundary conditions are based on the assumption that the infinite earth temperature $T \rightarrow T_\infty$ and the temperature at the center of the cable will be finite.

$$\theta_E = 0 \quad \theta \Big|_{\xi_E \rightarrow 1} \quad (\text{II.B.15})$$

$$\theta_c = \text{finite} \quad @ \xi_c \rightarrow 0 \quad (\text{II.B.16})$$

1. Steady State Temperature Distribution

The general solution of equation (II.B.5) in steady state ($\frac{\partial \theta}{\partial \tau} = 0$) is straight forward and can be written directly after integrating twice with respect to the dimensionless coordinate ξ . The general solution is

$$\theta = -H \frac{\xi^2}{4} + C_A \ln \xi + C_B$$

Where C_A and C_B are constants to be determined by the boundary conditions.

Applying the boundary condition equation (II.B.6) through (II.B.10) the steady state temperature distribution for each of the five materials is:

$$\theta_c = -H_c \frac{\xi_c^2}{4} + C_{10}$$

$$\theta_I = -H_I \frac{\xi_I^2}{4} + C_7 \ln \xi_I + C_8$$

$$\theta_s = -H_s \frac{\xi_s^2}{4} + C_4 \ln \xi_s + C_6$$

$$\theta_J = C_3 \ln \xi_J + C_4$$

$$\theta_E = C_1 \ln \xi_E$$

where

$$C_1 = C_3 \times \frac{k_J}{k_E} \times \frac{r_J}{r_E}$$

$$C_3 = \left(-\frac{H_S}{2} + C_5 \right) \frac{k_S}{k_J} \times \frac{k_S}{r_J}$$

$$C_4 = C_1 \ln \frac{r_J}{r_E}$$

$$C_5 = \left(-\frac{H_I}{2} k_I + C_7 k_I + H_S \times \frac{k_S}{2} \times \frac{r_I}{r_S} \right) \times \frac{r_I}{r_S} \times \frac{1}{r_S}$$

$$C_6 = C_3 \ln \frac{r_S}{r_J} + C_4 + \frac{H_S}{4}$$

$$C_7 = \left(-\frac{k_c}{k_I} \times \frac{H_c}{2} + \frac{H_I}{2} \times \frac{r_c}{r_I} \right) \times \frac{r_c}{r_I}$$

$$C_8 = -\frac{H_S}{4} \left(\frac{r_I}{r_S} \right)^2 + C_5 \ln \left(\frac{r_I}{r_S} \right) + C_6 + \frac{H_I}{4}$$

$$C_{10} = -\frac{H_I}{4} \left(\frac{r_c}{r_I}\right)^2 + C_7 \ln \left(\frac{r_c}{r_I}\right) + C_8 + \frac{H_c}{4}$$

2. Transient Temperature Distribution

Although the steady state temperature distribution in the cable is valuable information, one of the major objectives of this thesis is to determine the transient temperature in the cable during short-circuit conditions and under longer transients which occur because of normal load cycline of the cable. The steady state and transient solutions depend upon each other because the initial condition for the transient solution is assumed to be the steady state solution. That is, the transient behavior is assumed to occur after the cable has operated under steady state conditions and the temperature distribution has had a chance to become completely stable.

The steady state solutions to the general energy equation (II.B.5) is very involved and it requires a numerical technique. The numerical technique first selected for the transient solution was an explicit method. However, it was found that the method became unstable due to the small nodal spacing that was necessary, particularly in the shield material. To ensure stability, extremely short time intervals had to be used, and as a result, the computer time necessary to provide a sufficient amount of information became unreasonable.

To avoid the stability problem, an implicit method was selected. The implicit method consists of representing $\frac{\partial^2 \theta}{\partial \xi^2}$ and $\frac{\partial \theta}{\partial \xi}$ by finite difference forms evaluated at the advance time t_{n+1} . The difference equation for the differential equation (II.B.5) will be

$$\rho c \frac{T_i^{n+1} - T_i^n}{\Delta t} = k \left(\frac{T_{i-1}^{n+1} - 2T_i^{n+1} + T_{i+1}^{n+1}}{(\Delta r)^2} + \frac{1}{i\Delta r} \frac{T_{i+1}^{n+1} - T_{i-1}^{n+1}}{2(\Delta r)} \right) + H' \quad (\text{II.B.17})$$

for any node i .

Equation (II.B.17) gives a relationship between the value of temperature at the four points shown in the space-time grid of Figure 4

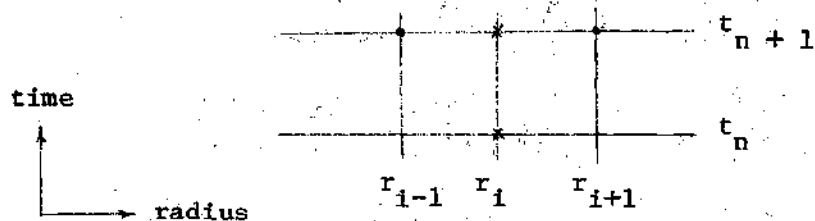


Figure 4. The Implicit Method.

by rearranging equation (II.B.17) it may be written in the form:

$$\begin{aligned} \frac{\Delta t k}{\rho c} \left(\frac{1}{2i(\Delta r)^2} - \frac{1}{(\Delta r)^2} \right) T_{i-1}^{n+1} + \frac{\Delta t k}{\rho c} \left(\frac{\rho c}{\Delta t k} + \frac{2}{(\Delta r)^2} \right) T_i^{n+1} \\ + \frac{\Delta t k}{\rho c} \left(-\frac{1}{2i(\Delta r)^2} - \frac{1}{(\Delta r)^2} \right) T_{i+1}^{n+1} = T_i^n + \frac{H' \Delta t}{\rho c} \quad (\text{II.B.18}) \end{aligned}$$

The initial condition for the transient solution is the previously obtained steady state solution or

$$T_i^0 = f(r_i)$$

where $f(r_i)$ represents the steady state temperature distribution.

At any one time interval equation (II.B.17) can be written once for each interior point (where $1 \leq i \leq M - 1$, where M represents the boundary node between two different materials). The procedure results in a system of $M - 1$ simultaneous algebraic equations in the $M - 1$ unknowns T_i^{n+1} . For the method used to solve the set of algebraic equations, see Appendix A.

The boundary conditions necessary for the transient solution will now be derived in a general form for the interface between two materials A and B. We wish to derive the relevant finite difference approximate for the temperature T_i at point i located on the interface between A and B. The procedure is based on the continuity of heat flux at the surface. Let A and B have thermal conductivity k_A , k_B and let the grid spacing in material A and B be Δr_A , Δr_B respectively. Suppose that the new temperature T_i' after a time increment Δt is to be calculated using an implicit representation.

By expanding the temperature in medium A in a Taylor's expansion at time $n+1$, we have approximately

$$T_{i-1}^{n+1} = T_i^{n+1} - \Delta r_A \left(\frac{\partial T}{\partial r} \right)_{iA} + \frac{(\Delta r_A)^2}{2} \left(\frac{\partial^2 T}{\partial r^2} \right)_{iA} \quad (\text{II.B.19})$$

where the subscript iA denotes the derivative in medium A evaluated at the interface that is

$$\left(\frac{\partial^2 T}{\partial r_A^2}\right)_{iA} = \frac{2}{(\Delta r_A)^2} \left(T_{i-1}^{n+1} - T_i^{n+1} + \Delta r_A \left(\frac{\partial T}{\partial r}\right)_{iA}\right) \quad (\text{II.B.20})$$

Also the time derivate is approximated by

$$\left(\frac{\partial T}{\partial t}\right)_{iA} = \frac{T_i^{n+1} - T_i^n}{\Delta t} \quad (\text{II.B.21})$$

The substitution of equation (II.B.20) and equation (II.B.21) into the unsteady state heat conduction equation (II.B.4) will result in

$$\frac{2}{(\Delta r_A)^2} \left(T_{i-1}^{n+1} - T_i^{n+1} + \Delta r_A \left(\frac{\partial T}{\partial r}\right)_{iA}\right) + \frac{1}{r_A} \left(\frac{\partial T}{\partial r}\right)_{iA} = \frac{1}{\alpha_A} \left(\frac{T_i^{n+1} - T_i^n}{\Delta t}\right) - \frac{H'_A}{K_A} \quad (\text{II.B.22})$$

so solving for the radial temperature gradient at the interface yields:

$$\left(\frac{\partial T}{\partial r}\right)_{iA} = \frac{-\frac{2}{(\Delta r_A)^2} \left(T_{i-1}^{n+1} - T_i^{n+1}\right) + \frac{1}{\alpha_A} \left(\frac{T_i^{n+1} - T_i^n}{\Delta t}\right) - \frac{H'_A}{K_A}}{\frac{2}{(\Delta r_A)} + \frac{1}{r_A}} \quad (\text{II.B.23})$$

Using the same procedure for the radial gradient of temperature at the interface in media B yields

$$-\left(\frac{\partial T}{\partial r}\right)_{iB} = \frac{-\frac{2}{(\Delta r_B)^2} (T_{i+1}^{n+1} - T_i^{n+1}) + \frac{1}{\alpha_B} \left(\frac{T_i^{n+1} - T_i^n}{\Delta t}\right) - \frac{H'_B}{k_B}}{\left(\frac{2}{(\Delta r_B)} + \frac{1}{r_B}\right)} \quad (\text{II.B.24})$$

The unwanted derivatives $\left(\frac{\partial T}{\partial r}\right)_{iA}$ and $\left(\frac{\partial T}{\partial r}\right)_{iB}$ may now be eliminated by observing that the heat flux must be continuous at the interface, so that

$$k_A \left(\frac{\partial T}{\partial r}\right)_{iA} = k_B \left(\frac{\partial T}{\partial r}\right)_{iB} \quad (\text{II.B.25})$$

Then, by substituting equation (II.B.23) and (II.B.20) into equation (II.B.25) and simplifying produces the desired difference boundary condition

$$\begin{aligned} & \left(\frac{-2k_A}{(\Delta r_A)^2} \left(\frac{2}{\Delta r_B} + \frac{1}{r_B}\right)\right) T_{i-1}^{n+1} + \left(\frac{2k_A}{(\Delta r_A)^2} + \frac{k_A}{\alpha_A \Delta t}\right) \left(\frac{2}{\Delta r_B} + \frac{1}{r_B}\right) T_i^{n+1} + \left(\frac{-2k_B}{(\Delta r_B)^2} + \frac{k_B}{\alpha_B \Delta t}\right) \left(\frac{2}{\Delta r_A} + \frac{1}{r_A}\right) T_i^{n+1} + \left(\frac{2k_B}{(\Delta r_B)^2} \left(\frac{2}{\Delta r_A} + \frac{1}{r_A}\right)\right) T_{i-1}^{n+1} = \\ & \left(\frac{k_A}{\alpha_A \Delta t} \left(\frac{2}{\Delta r_B} + \frac{1}{r_B}\right) + \frac{k_B}{\alpha_B \Delta t} \left(\frac{2}{\Delta r_A} + \frac{1}{r_A}\right)\right) T_i^n + H'_A \left(\frac{2}{\Delta r_B} + \frac{1}{r_B}\right) + H'_B \left(\frac{2}{\Delta r_A} + \frac{1}{r_A}\right) \end{aligned} \quad (\text{II.B.26})$$

Equation (II.B.26) is the general form of the boundary condition and it is applied to the four interfaces between the five different materials which make up the cable system. Also the continuity of temperature at all interfaces will be boundary conditions just as in the steady state problem. The final two boundary conditions are based on the assumption that the ambient earth temperature and the temperature at the center of the cable will be finite.

$$a. T_E = T_\infty \quad @ r_E \rightarrow \infty$$

$$b. T_C = \text{finite} \quad @ r_C = 0$$

C. Electrical Considerations

Some of the factors affecting the temperature distribution in underground cables cannot be expressed completely in terms of heat transfer considerations. For example, the induced currents in the shield material and the heat generation by current flow in the insulating materials must be evaluated from a knowledge of electrical considerations. The purpose of this section is to express the electrical factors which must be put into the general energy equation in terms of measurable input parameters.

1. Effect Of Induced Current

According to Neher McGrath [1], the total temperature rise in a cable is due to the dielectric loss (ΔT_d) and current produced losses (ΔT_c) in the conductor and shield. Thus

$$\Delta T = \Delta T_c + \Delta T_d \quad (\text{II.C.1})$$

Simmons [2] has indicated that the losses due to induced sheath currents occur physically in the cable sheath and thus the heat does not have to flow through the thermal resistance between conductor and sheath. The heat does, however, flow through the other two thermal resistances namely that between sheath and duct wall and that between duct and earth causing increased temperature rise in these places. Mathematically, this can be handled by including the effect of the induced sheath currents as an apparent increase in thermal resistance of the latter two elements. Thus

$$\Delta T_c = W_c (\hat{R}_i + q_s \hat{R}_{se} + q_e \hat{R}_e) \quad (\text{II.C.2})$$

where W_c = losses in one conductor

\hat{R}_i = thermal resistance of the insulator

q_s = the ratio of the sum of the losses in the conductor and shield to the losses in the conductor $\frac{W_c + W_s}{W_c}$

\hat{R}_{se} = the total thermal resistance between sheath and conduit

q_c = the ratio of the sum of the losses in conductors, sheath and conduit to the conductor losses

\hat{R}_e = thermal resistance between the conduit and ambient.

In practice, the load carried by a cable is rarely constant and varies according to a daily load cycle having a load factor (lf). The load factor of a system is defined as the ratio of the average power of

the system to the maximum power over a certain period of time (say, one year). Hence, the losses in the cable will vary according to the corresponding daily loss cycle having a loss factor (LF). The relationship between lf and LF is [18]

$$LF = 0.3 (lf) + 0.7 (lf)^2$$

2. Effective Thermal Resistance Of The Earth

The analysis presented here is limited to one dimensional conduction and mutual heating between two or more cables must be accommodated by defining an effective resistivity of the soil. This effective thermal resistance includes the effect of the loss factor and in the case of multi-cable installations, the mutual heating effects of the other cables of the system. The following expression was used for the effective soil resistance [1]:

$$R_e' = \frac{1}{K} N' \times \log \frac{D_x}{D_e} + (LF) \log \left(\frac{4L}{D_x} F \right) \quad (\text{II.C.3})$$

In this equation, D_e is the diameter at which N' is number of conductors contained within the radius D_e , and L is the depth the cable is buried below the surface of the earth. The effect of D_x is eliminated when the loss factor is unity. The factor F accounts for the mutual heating effect of the other cables of the cable system, and consists of the product of the ratio of the distance from the reference cables to

the image of each of the other cables to the distance to that cable [1].

$$F = \frac{d'_{12}}{d_{12}} \frac{d'_{13}}{d_{13}} \dots \frac{d'_{IN}}{d_{IN}} \quad (\text{II.C.4})$$

It will be noted that the value of F will vary depending upon which cable is selected as the reference. See Appendix B for a complete derivation of the factor F for various cable arrangements treated in this thesis.

Equation (II.C.3) enables us to calculate the mutual heating effect F with respect to the losses q_s given in equations (II.C.2) for each conductor. Each term of equation (II.C.4) can be separated and multiplied by the losses q_s . For $N' = 1$ and three cables with the reference cable being the middle one, the expression for R_e given by equation (II.C.3) may be written as

$$\hat{R}_{e1} = \frac{1}{K} \log \frac{D}{D_e} + (LF) \frac{1}{k} \log \frac{4L}{D_x} + (LF) \frac{1}{k} \log F \quad (\text{II.C.5})$$

If we let $\hat{R}_{x1} = \frac{1}{k} \left(\log \frac{D}{D_e} \right)$

$$\hat{R}_{x2} = (LF) \frac{1}{k} \left(\log \frac{4L}{D_x} \right)$$

$$\hat{R}_{21} = (LF) \frac{1}{k} \left(\log \frac{D_{21'}}{D_{21}} \right)$$

$$\hat{R}_{23} = (LF) \frac{1}{k} \left(\log \frac{D_{23'}}{D_{23}} \right)$$

then the total resistance of the earth is

$$R_e = q_{s_1} (R_{x1} + R_{x2}) + q_{s_2} (R_{21}) + q_{s_3} (R_{23}) \quad (\text{II.C.6})$$

$$\text{where } q_{s_i} = 1 + \left(\frac{\text{current in the shield}}{\text{current in the conductor}} \right)^2 \frac{R_{s_i}}{R_{dc}}$$

and i refers to the three cables ($i = 1, 2, 3$).

3. Electrical Resistance Due To Variable Temperature

It is necessary to correct the electrical resistance for temperature in most problems. The resistance of copper is proportional to $234 + T$, where T is the conductor temperature in deg C. The resistance of copper at any temperature T can therefore be calculated relative to 25°C by the equation

$$R_{dc} = \frac{234 + T}{259} \times R_{25} \quad (\text{II.C.7})$$

Similarly, the resistance of aluminium may be expressed as

$$R_{dc} = \frac{228 + T}{253} \times R_{25} \quad (\text{II.C.8})$$

4. Skin Effect

The resistance provided by equation (II.C.7) and (II.C.8) is the dc resistance in a conductor. Since the cable carries alternating current,

the ac resistance must be used in any equation which provides heating losses. The ac resistance is evaluated by calculating the conductor skin effect. The skin effect is a measure of the increase in resistance because there is a tendency for the current density to decrease toward the center axis of the conductor and because the current in the different conductor layers changes due to an increase of inductance toward the center of the cable.

The skin effect which is the ratio of ac to dc resistance may be determined from the skin effect function $F(x_s)$ [1]

$$Y_c = F(X_s) = \frac{R_{ac}}{R_{dc}}$$

where

$$X_s = \frac{6.80}{\sqrt{R_{dc}/K_s}}$$

at 60 hertz.

The factor k_s depends upon the conductor construction. For solid or conventional conductors appropriate values of K_s can be found in Table 2. The function $F(X_s)$ may be obtained from Table 3. The ac energy generation in the conductor can now be expressed in terms of the skin effect as:

$$H' = \rho_e \left(\frac{I^2}{A_c} \right)^2 Y_c$$

Table 2. Recommended Values Of K_s
(From Reference 2)

Conductor	Construction	Coating on Strands	Treatment	K_s
Concentric	Round	None	None	1.0
Concentric	Round	Tin or Alloy	None	1.0
Concentric	Round	None	Yes	1.0
Compact	Round	None	Yes	1.0
Compact	Segmental	None	None	0.435
Compact	Segmental	Tin or Alloy	None	0.5
Compact	Segmental	None	Yes	0.435
Compact	Sector	None	Yes	1.0

Table 3. Skin Effect In % For Solid Round Conductor
And Conventional Round Concentric Strand Conductor (From Reference 2)

x	F(x)	x	F(x)	x	F(x)
0.3	0.00	1.6	3.32	2.9	28.65
0.4	0.01	1.7	4.21	3.0	31.81
0.5	0.03	1.8	5.24	3.1	35.10
0.6	0.07	1.9	6.44	3.2	38.50
0.7	0.12	2.0	7.82	3.3	42.00
0.8	0.21	2.1	9.38	3.4	45.57
0.9	0.34	2.2	11.13	3.5	49.20
1.0	0.52	2.3	13.07	3.6	52.88
1.1	0.76	2.4	15.21	3.7	56.59
1.2	1.07	2.5	17.54	3.8	60.31
1.3	1.47	2.6	20.06	3.9	64.05
1.4	1.97	2.7	22.75	4.0	67.79
1.5	2.58	2.8	25.62	4.1	71.52

A similar expression may be written for the heat generated in the shield material.

5. Dielectric Losses

The dielectric loss W_d for a single-conductor cable is given by the expression [1]

$$W_d = \frac{9.055 \times 10^{-5} E^2 \epsilon_r \cos \phi}{\log (2T_I + D_c)/D_c}$$

where E is the phase to neutral voltage in kilovolts, ϵ_r is the specific inductive capacitance of the insulation (see Table 4 for values), T_I is the insulation thickness, $\cos \phi$ is its power factor and D_c is the diameter of conductor.

6. Shield Losses

The energy generated in the shield is proportional to the shield resistance and the square of the shield current. Therefore, the losses in the shield material can only be calculated after the current in the shield is known.

For the usual arrangements of one and two circuits of single-conductor cables buried in the earth, Halperin and Miller [11] have given applicable formulas for the currents induced in the shield material. Table 5 is taken directly from their work with numerical magnitudes substituted for the vector ratios. The equations in the table were used to provide values of I_s to be substituted in equation (II.B.8).

Table 4. Specific Inductive Capacitance
Of Insulations (From Reference 2)

Material	ϵ_r
Paper insulations (solid)	3.7
Paper insulation (other type)	3.3-4.2
Rubber and rubber-like compounds	5
Varnished cambric	5

Table 5. Formulas For Sheath Currents (From Reference 11).

Cable Arrangement Number and Diagram	I One Phase	II Equilateral	III Rectangle	IV Flat	V Two Circuit	VI Two Circuit
	B A S + +	A B C S + +	A B C S + +	A B C S S + +	A B C S S + + A B C	C B A S S + + A B C
Current $\frac{I_A}{I} =$	$\frac{X_M^2}{R_s^2 + X_M^2}$	$\frac{X_M^2}{R_s^2 + X_M^2}$		$\frac{(P^2 + 3\theta^2) + 2\sqrt{3}(P - \theta) + 4}{4(p^2 + 1)(\theta^2 + 1)}$		
Current $\frac{I_B}{I} =$	$\frac{X_M^2}{R_s^2 + X_M^2}$	$\frac{X_M^2}{R_s^2 + X_M^2}$		$\frac{1}{(\theta^2 + 1)}$		
Current $\frac{I_C}{I} =$		$\frac{X_M^2}{R_s^2 + X_M^2}$		$\frac{(P^2 + 3\theta^2) - 2\sqrt{3}(P - \theta) + 4}{4(p^2 + 1)(\theta^2 + 1)}$		
where		$Y = X_M$	$(X_M + \frac{a}{b})$	$(X_M + a)$	$(X_M + a + \frac{b}{2})$	$(X_M + a - \frac{b}{2})$
$p = \frac{RS}{Y} = \frac{RS}{Z}$		$Z = X_M$	$(X_M - \frac{a}{b})$	$(X_M + \frac{a}{b})$	$(X_M + \frac{a}{b} - \frac{b}{6})$	$(X_M + \frac{a}{b} - \frac{b}{6})$
			$a = 0.153333$ (60 cycles)			
			$b = 0.03699617$ (60 cycles)			
			$X_M = 0.05292 \log_{10} (\frac{S}{r_m})$			

I = current in the conductor, amps.
 I_{A,B,C} = current in the shield, amps.

r_m = mean radius of sheath, inches.
 S = spacing between center line of cables, inches.

R_s = resistance of sheath, ohm per 1000 ft.

CHAPTER III

COMPUTER PROGRAM

A. Program Objectives And Capabilities

This section describes the computer program used to calculate both steady state and transient temperature distribution in underground electrical power cables. The first section describes the program in general. The second section lists all input data and the third section describes how a potential user can use the program.

The entire program consists of 12 separate subprograms and data sets. The source language is Extended FORTRAN IV.

B. Alphabetical List Of Input Data

All input variables needed for program operation are listed below along with their units and a brief description of the meaning of the variables.

Variable Name	Units	Referenced in Program Unit	Description
CPA	watt-sec/gm°C	THRMPRP	Specific heat of air
CPC	watt-sec/gm°C	THRMPRP	Specific heat of conductor
CPE	watt-sec/gm°C	ERTHPRP	Specific heat of earth
CPI	watt-sec/gm°C	THRMPRP	Specific heat of insulator
CPO	watt-sec/gm°C	THRMPRP	Specific heat of jacket

Variable Name	Units	Referenced in Program Unit	Description
CPS	watt-sec/gm°C	THRMPRP	Specific heat of shield
DEPTH	cm	CBLGEO	The distance between cables and ground
DIACW	cm	CBLGEO	Diameter of conductor wire
DIACW	cm	CBLGEO	Diameter of shield wire
FAULTI	Amps	ELECPRP	Fault current
IARNGE	Dimensionless	CBLGEO	Cable configuration
ICBL	Dimensionless	CBLGEO	The material of conductor
ICNTRL	Dimensionless	CBLGEO	The control to calculate steady state or transient
ISHLD	Dimensionless	CBLGEO	The type of shield
II	Amps	ELECPRP	Current in the cable
KA	watt/cm°C	THRMPRP	Thermal conductivity of air
KC	watt/cm°C	THRMPRP	Thermal conductivity of conductor
KE	watt/cm°C	ERTHPRP	Thermal conductivity of earth
KI	watt/cm°C	THRMPRP	Thermal conductivity of insulation
KO	watt/cm°C	THRMPRP	Thermal conductivity of jacket
KS	watt/cm°C	THRMPRP	Thermal conductivity of shield
LAY	cm	CBLGEO	Lay of wire shield
LOADF	Dimensionless	ELECPRP	Load factor
NC	Dimensionless	CBLGEO	Number of wires in conductor
NSW	Dimensionless	CBLGEO	Number of wires in shield

Variable Name	Units	Referenced in Program Unit	Description
OVRLAP	cm	CBLGEO	Overlap of shield material
PAREA	Dimensionless	CBLGEO	Percent area of total surface of shield wires in contact with jacket material
PF	Dimensionless	ELECPRP	Power factor of insulator
RC	cm	CBLGEO	Outside radius of conductor
RE	cm	ERTHPRP	Radius of earth to location where $T = TEF$
RI	cm	CBLEGO	Outside radius of insulator
RO	cm	CBLEGO	Outside radius of jacket
RS	cm	CBLEGO	Outside radius of shield
RESA	OHM-cm	ELECPRP	Electric resistivity of air at 75°C
RESC	OHM-cm	ELECPRP	Electric resistivity of conductor at 25°C
RESS	OHM-cm	ELECPRP	Electric resistivity of shield at 25°C
RHOA	gm/cc	THRMPRP	Density of air
RHOC	gm/cc	THRMPRP	Density of conductor
RHOE	gm/cc	ERTHPRP	Density of earth
RHOI	gm/cc	THRMPRP	Density of insulator
RHOO	gm/cc	THRMPRP	Density of jacket
RHOS	gm/cc	THRMPRP	Density of shield
S	cm	CBLEGO	Spacing between center line of cables
SPCAP	Dimensionless	ELECPRP	Specific capacitance of dielectric

Variable Name	Units	Referenced in Program Unit	Description
TEF	°C	ERTHPRP	Temperature of ambient earth
TOFF	SEC	ELECPRP	Time current is open
TON	SEC	ELECPRP	Time current is close
VOLT	VOLT	ELECPRP	Line to neutral voltage

C. Namelist

The namelist data strings must be sequenced in the order in which they are listed below. The CGS system of units is used consistently for all quantities. All input data are specified by the following four namelists.

1. Namelist CBLGEO contains 17 variables, which define the geometry of the cable system:

RC	Outside radius of cable conductor in cm
RI	Outside radius of cable insulator in cm
RS	Outside radius of cable shield in cm
RO	Outside radius of jacket in cm
S	Spacing between each cable in cm
ISHLD=1	Solid shield
ISHLD=2	Wire shield
IARNGE=1	Two cables straight - one phase
IARNGE=2	Three cables - equilateral triangle
IARNGE=3	Three cables - right triangle
IARNGE=4	Three cables - straight line

IARNGE=5	Six cables - opposed, two circuit flat
IARNGE=6	Six cables - flat reversed phase
(see Figure 5 for the six cable arrangements)	
NC	Number of wires in conductor
DIACW	Diameter of conductor wire in cm
DIASW	Diameter of shield wire in cm
NSW	Number of wire in shield
ICBL=1	Copper conductor
ICBL=2	Aluminium conductor
DEPTH	The depth of cables under ground in cm
PAREA	Percent area of total surface of shield wire in contact with jacket material
OVRLAP	Overlap of shield material
LAY	Lay of wire shield
ICNTRL	The control to calculate steady state or transient condition

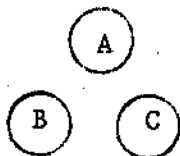
2. Namelist/THRMPRP/contains 15 variables, which define the thermal properties of cable materials:

KC	Thermal conductivity of conductor in watt/cm°C
KI	Thermal conductivity of insulator in watt/cm°C
KO	Thermal conductivity of jacket in watt/cm°C
KS	Thermal conductivity of shield in watt/cm°C
KA	Thermal conductivity of air in watt/cm°C
RHOC	Density of conductor in gm/cc
RHOI	Density of insulator in gm/cc
RHOS	Density of shield in gm/cc

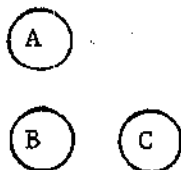
I. One Phase



II. Equilateral



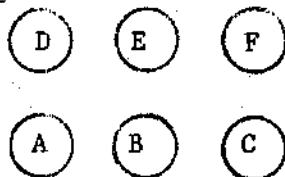
III. Right Triangular



IV. Flat



V. Two Circuit Flat



VI. Two Circuit Flat Reversed Phase

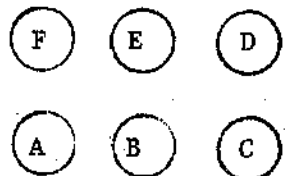


Figure 5. Six arrangements of Cables.

RHOO	Density of jacket in gm/cc
RHOA	Density of air in gm/cc
CPA	Specific heat of air in watt-sec/gm°C
CPC	Specific heat of conductor in watt-sec/gm°C
CPI	Specific heat of insulator in watt-sec/cm°C
CPS	Specific heat of shield in watt-sec/gm°C
CPO	Specific heat of jacket in watt-sec/gm°C

3. Namelist/ELECPRP/contains 11 variables which define the electrical properties necessary to determine the temperature distribution:

SPCAP	Specific of capacitance of dielectric
II	Current in the cable in amp
VOLT	Line to neutral voltage in volt
PR	Power factor of insulator
LOADF	Load Factor
FAULTI	Fault current when short occurs in amps
TON1	Length of first short circuit in sec
TON2	Length of second short circuit in sec
TON3	Length of third short circuit in sec
TOFF1	Length of first open circuit in sec
TOFF2	Length of second open circuit in sec

4. Namelist/ERTHPRP/contains 4 variables which define the properties of the earth:

KE	Thermal conductivity of earth in watt/cm°C
CPE	Specific heat of earth in watt-sec/gm°C
RHOE	Density of earth in gm/cc
TEF	Temperature of ambient earth in °C

D. Description Of Program

The computer program consists of a main program element and 12 subprograms. This section describes each of these program elements by discussing the function of each element. The subprograms are listed in alphabetical order.

1. Main - the main program unit which
 - provides: a. input and output
 - b. steady state and transient temperature distribution
 - calls: a. CURSHLD - current in the shield
 - b. HTSORCE - Fourier number and heat source for each section
 - c. KEQUV - equivalent thermal conductivity of composite shield
 - d. function subprograms for material properties
2. Subroutine CURSHLD (RCOND, RSHLD, ISA, ISB, ISC, QSA, QSB, QSC) - calculates the induced current in the shield
 - receives: a. dc electrical resistance of conductor per cm length with different temperature, RCOND
 - b. dc electrical resistance of shield per cm length with different temperature, RSHLD
 - provides: a. induced current in the shield of cables A, B, C; ISA, ISB, ISC respectively
 - b. the ratio of the sum of the losses in the conductor and shield to the losses in the conductor of cables A, B, C; QSA, QSB, QSC,

3. Function DINF (IS, TOUT, RCOND, RSHLD) - which calculates the diameter of the earth where temperature T_{∞} is measured in cm receives:
- a. current in the shield, IS
 - b. temperature of the outside surface of the cable, TOUT
 - c. resistance of the conductor, RCOND
 - d. resistance of the shield, RSHLD

Presently this subprogram uses a constant value for DINF without calculation of a value in the subprogram.

4. Function DIELOS (VOLT, SPCAP, PF, RC, RI) - which calculates losses in dielectric in watt/cm receives:
- a. phase to neutral voltage, VOLT
 - b. specific capacitance of dielectric, SPCAP
 - c. power factor of insulator, PF
 - d. outside radius of conductor, RD
 - e. outside radius of insulator, RI
5. Function EFFKE (DINFIN, QSA, QSB, QSC, M, LOADF) - which evaluates the effective thermal conductivity of soil actual k of soil is modified to account for mutual heating between adjacent cables in watt/cm C receives:
- a. distance from outside jacket to $T = TEF$, DINFIN
 - b. which cable, M, Load Factor, LOADF
 - c. ratio of the sum of the losses in the conductor and shield to the losses in the conductor of cable A, B, C; QSA, QSB, QSC, respectively

6. Subroutine HTSORCE (IS, IM, TON, RCOND, RSHLD, SKEFF, DLOSS, HSC, HSI, HSS, FOC, FOI, FOS, FOO, FOE) - which calculates the heat source and Fourier number for conductor, insulator and shield. Both are dimensionless

receives: a. current in the shield, IS
b. current in the conductor, IM
c. time circuit is faulted, TON
d. dc electrical resistance of conductor per cm length with difference temperature, RCOND
e. dc dielectrical resistance of shield per cm length with difference temperature, RSHLD
f. skin effect, SKEFF

provides: a. heat source, dimensionless
b. Fourier number, dimensionless

7. Subroutine KEQUV (KS, KA, RI, RS, DIASW, NSW) - which calculates equivalent thermal conductivity of shield and air gap when shield consists of wires in watt/cm C

receives: a. thermal conductivity of shield (copper), KS
b. thermal conductivity of air, KA
c. outside radius of insulator, RI
d. outside radius of shield, RS
e. diameter of shield wire, DIASW
f. number of shield wire, NSW

provides: a. equivalent thermal conductivity of shield

8. Function RESCOND (TCOND, NC, DIACW, ICBL) - which calculates dc electrical resistance of conductor per cm length in ohm/cm

and accounts for variation of resistance with conductor temperature. Both aluminum and copper conductors are considered

receives: a. solid shield or wire shield, ISHLD
 b. number of shield wire, NSW
 c. diameter of shield wire, DIASW
 d. guess temperature of shield, TSHLD
 e. outside radius of insulator, RI
 f. outside radius of shield, RS
 g. overlap of shield material, OVLAP
 h. lay of wire shield, LAY

10. Function SKINEFF (RCOND) - which calculates skin effect, ratio of ac to dc resistance dimensionless

receives: a. dc electrical resistance of conductor per cm length with different temperature, RCOND

11. Subroutine TRIDAG (IF, L, A, B, C, D, V) - which solves a system of linear simultaneous algebraic equations by a tri-diagonal coefficient matrix

receives: a. integer corresponding to the first subscripts, IF
 b. integer corresponding to the last subscripts, L
 c. coefficient vector A
 d. vector containing the computed solution, V

provide: a. solution of simultaneous equations

12. Function YINT (X, Y, N, M, P) - which is used interpolate in a set of tabular values

receives: a. X and Y are the names of arrays that have the

same dimension M and contain the ordered pairs (X_i, Y_i) , $i = 1, 2, \dots, M$ such that $x_1 < x_2 < \dots < x_M$

- b. the number n of points used for the interpolation is specified as N
- c. the value of X at which to interpolate is supplied as P . note: $2 \leq N \leq M$ must be satisfied

E. Sample Output

This section shows input variables and the resulting output for a typical cable system. Both steady state and transient temperature results are shown.

The first four pages show the input namelists: CBLGEO (cable geometry), THRMGRP (thermal properties), ELECGRP (electrical properties), and ERTHGRP (earth properties). The input variables coincide to three straight cables buried directly in the earth at a depth of 122 cm and on 20.32 cm centers. Each cable has a 1 million circular mil conductor covered by a cross linked polyethylene (XLP) insulator. The shield consists of 14 no. 16 gauge copper wires. The jacket is made of semi-conducting polyethylene (SCP) and it contacts the shield were over 75% of its area. The cable voltage is 25,000 volts phase to phase or 14,434 volts phase to neutral. The soil has a typical value of thermal conductivity experienced in field applications.

After the input values are listed, the next page gives values for selected output variables. The definitions of the computer symbols are

given in the comment statements which precede the main program unit.

The next page of output provides the steady state temperature distribution for the center cable (cable number 2). The conductor and shield temperature are practically isothermal at approximately 46°C and 45°C . The ambient earth temperature was selected at 25°C resulting in a maximum temperature rise of 21°C .

The next five pages of output give the transient temperature distribution in the cable and earth at the end of five short circuit sequences. The first, third and fifth page gives the temperature after the fault current has passed through the conductor and shield. For this example, the fault current is 8,394.0 amps. The second and fourth page of transient output gives the temperature after the circuit has been opened and the current has dropped to zero. The cycle times are assumed to be the following values: current on for 0.125 sec, off for 4.23 sec, on for 0.183 sec, off for 11.7 sec and finally on for 0.2 sec. These times are listed at the top of each output page. The maximum temperature during the short circuit sequence always occurs in the shield due to the large currents in the shield wires and a resistance which is higher than the conductor. The highest temperature in the shield is 300°C after the end of the third circuit closure.

\$CBLGEO

RC = .14465E+01,
 RI = .20942E+01,
 RS = .22237E+01,
 RO = .252854E+01,
 S = .2032E+02,
 ISHLD = 2,
 IARNGE = 4,
 NG = 61,
 DIACH = .32512E+00,
 DIASH = .12954E+00,
 NSW = 14,
 ICBL = 2,
 DEPTH = .122E+03,
 PAREA = .75E+00,
 OVRLAP = .127E+01,
 LAY = .1E+03,
 ICNTRL = 2,

\$END

\$SELEPRP

SPCAP = .35E+01,
 II = .3E+03,
 VOLT = .14434E+05,
 PF = .22E-01,
 LOADF = .1E+01,
 FAULTI = .8394E+04,
 TON1 = .125E+00,
 TON2 = .1833E+00,
 TON3 = .2E+00,
 TOFF1 = .423E+01,
 TOFF2 = .117E+02,

\$END

\$THRMPRP

KC = .2042E+01,
 KI = .2894E-02,
 KO = .24757E-02,
 KS = .381E+01,
 KA = .277E-03,
 RHOC = .27E+01,
 RHOI = .1E+01,
 RHOS = .896E+01,
 RHOO = .115E+01,
 RHOA = .78E-03,
 CPA = .10207E+01,
 CPC = .8708E+00,
 CPI = .239E+00,
 CPS = .3809E+00,
 CPO = .27E+01,

\$END

\$ERTHPRP

KE = .11111E-01,
 CPE = .184E+01,
 RHOE = .144E+01,
 TEF = .25E+02,

\$END

RESCOND=	.6000487E+06
RESHLD=	.1019323E+04
SKINEFF=	-1024775E+01
ISA =	.5756032E+02
ISB =	.4432716E+02
ISC =	.6027456E+02
ISA =	.1619277E+01
OSB =	.1365991E+01
OSC =	.1676704E+01
ISA =	.5756032E+02
ISH =	.4432716E+02
ISC =	.6027456E+02
USA =	.1619277E+01
OSH =	.1365991E+01
OSC =	.1676704E+01
EFFKE =	.6900402E-03
HSC =	.4530814E-03
HSS =	.3469240E-01
HSI =	.7605387E-01
FOC =	0.
FOS =	0.
FOI =	0.
FOO =	0.
FOE =	0.
C1 =	-.80332E+00
C3 =	-.55756E+00
C4 =	.72605E+00
C5 =	.14810E-01
C6 =	.80635E+00
C7 =	-.92461E-01
C8 =	.81678E+00
C10 =	.84204E+00

CABLE 2

STEADY STATE TEMPERATURE DISTRIBUTION (DEG. C) AS A FUNCTION OF RADIAL POSITION (CM)

EARTH		JACKET		SHIELD		INSULATOR		CONDUCTOR	
RADIUS	TEMP	RADIUS	TEMP	RADIUS	TEMP	RADIUS	TEMP	RADIUS	TEMP
6.25000	25.00000	2.52854	43.15119	2.22370	44.94193	2.09420	44.94424	1.44650	46.04812
6.39494	25.50391	2.51584	43.22139	2.21830	44.94208	2.06721	44.98639	1.38623	46.04835
5.93988	26.02080	2.50314	43.29194	2.21291	44.94223	2.04023	45.02878	1.32596	46.04857
5.78482	26.55137	2.49043	43.36285	2.20751	44.94237	2.01324	45.07142	1.26569	46.04879
5.62976	27.09636	2.47773	43.43413	2.20212	44.94251	1.98625	45.11431	1.20542	46.04899
5.47470	27.65656	2.46503	43.50577	2.19672	44.94264	1.95926	45.15748	1.14515	46.04918
5.31963	28.23287	2.45233	43.57778	2.19132	44.94277	1.93228	45.20092	1.08488	46.04936
5.16457	28.82622	2.43963	43.65016	2.18593	44.94289	1.90529	45.24466	1.02460	46.04953
5.00951	29.43767	2.42693	43.72292	2.18053	44.94301	1.87830	45.28870	.96433	46.04970
4.85445	30.06834	2.41422	43.79606	2.17514	44.94312	1.85131	45.33306	.90406	46.04985
4.69939	30.71948	2.40152	43.86959	2.16974	44.94323	1.82433	45.37776	.84379	46.04999
4.54433	31.39248	2.38882	43.94351	2.16435	44.94334	1.79734	45.42290	.78352	46.05013
4.38927	32.09884	2.37612	44.01783	2.15895	44.94344	1.77035	45.46821	.72325	46.05025
4.23421	32.81625	2.36342	44.09254	2.15355	44.94353	1.74336	45.51399	.66298	46.05036
4.07915	33.55857	2.35072	44.16765	2.14816	44.94362	1.71638	45.56018	.60271	46.05047
3.92409	34.33591	2.33802	44.24317	2.14276	44.94370	1.68939	45.60677	.54244	46.05056
3.76903	35.14458	2.32531	44.31911	2.13737	44.94378	1.66240	45.65380	.48217	46.05064
3.61397	35.98724	2.31261	44.39545	2.13197	44.94386	1.63541	45.70128	.42190	46.05072
3.45891	36.86685	2.29991	44.47222	2.12658	44.94393	1.60843	45.74923	.36163	46.05078
3.30384	37.78681	2.28721	44.54942	2.12118	44.94399	1.58144	45.79768	.30135	46.05083
3.14878	38.75101	2.27451	44.62704	2.11578	44.94405	1.55445	45.84664	.24108	46.05088
2.99372	39.76390	2.26181	44.70510	2.11039	44.94410	1.52746	45.89614	.18081	46.05091
2.83866	40.83068	2.24910	44.78360	2.10499	44.94415	1.50048	45.94620	.12054	46.05094
2.68360	41.95740	2.23640	44.86254	2.09960	44.94420	1.47349	45.99635	.06027	46.05095
2.52854	43.15119	2.22370	44.94193	2.09420	44.94424	1.44650	46.04812	0.00000	46.05096

RESCOND= .6170887E-06
 RESSHLD= .1035543E-04
 HSC = .3606177E+00
 HSS = .1263831E+04
 HSI = .7605387E-01
 FOC = .9310952E-01
 FOS = .4583967E-02
 FOI = .3461233E-03
 FOO = .1558859E-04
 FOE = .8406283E-06

LOCAL TEMPERATURE DEGREES CENTIGRADE TIME IS .125E+00 SEC

EARTH		JACKET		SHIELD		INSULATOR		CONDUCTOR	
RADIUS	TEMP	RADIUS	TEMP	RADIUS	TEMP	RADIUS	TEMP	RADIUS	TEMP
6.25000	25.00000	2.52854	43.15583	2.22370	180.02574	2.09420	183.27707	1.44650	46.90363
5.09494	25.50392	2.51584	43.22227	2.21830	183.36754	2.06721	107.59082	1.38623	46.90581
5.93988	26.02082	2.50314	43.29190	2.21291	180.69222	2.04023	70.44953	1.32596	46.90776
5.78482	26.55139	2.49043	43.36263	2.20751	180.99975	2.01324	54.38366	1.26569	46.90948
5.62976	27.09637	2.47773	43.43387	2.20212	181.29008	1.98625	48.21578	1.20542	46.91099
5.47470	27.65658	2.46503	43.50550	2.19672	181.56316	1.95926	46.10409	1.14515	46.91230
5.31963	28.23289	2.45233	43.57750	2.19132	181.81892	1.93228	45.46747	1.08488	46.91342
5.16457	28.82624	2.43963	43.64988	2.18593	182.05728	1.90529	45.31400	1.02460	46.91434
5.00951	29.43769	2.42693	43.72263	2.18053	182.27815	1.87830	45.30501	.96433	46.91508
4.85445	30.06836	2.41422	43.79577	2.17514	182.48141	1.85131	45.33602	.90406	46.91563
4.69939	30.71950	2.40152	43.86929	2.16974	182.66692	1.82433	45.37753	.84379	46.91599
4.54433	31.39250	2.38882	43.94321	2.16435	182.83453	1.79734	45.42181	.78352	46.91616
4.38927	32.08886	2.37612	44.01751	2.15895	182.98408	1.77035	45.46701	.72325	46.91613
4.23421	32.81028	2.36342	44.09222	2.15355	183.11538	1.74336	45.51278	.66298	46.91588
4.07915	33.55861	2.35072	44.16732	2.14816	183.22822	1.71638	45.55881	.60271	46.91540
3.92409	34.33594	2.33802	44.24284	2.14276	183.32236	1.68939	45.60534	.54244	46.91465
3.76903	35.14462	2.32531	44.31977	2.13737	183.39754	1.66240	45.65235	.48217	46.91360
3.61397	35.98728	2.31261	44.39522	2.13197	183.45350	1.63541	45.70000	.42190	46.91219
3.45891	36.86689	2.29991	44.47310	2.12658	183.48991	1.60843	45.74885	.36163	46.91034
3.30384	37.78686	2.28721	44.56116	2.12118	183.50645	1.58144	45.80077	.30135	46.90792
3.14878	38.75106	2.27451	44.73350	2.11578	183.50275	1.55445	45.86138	.24108	46.90473
2.99372	39.76396	2.26181	45.53443	2.11039	183.47841	1.52746	45.94588	.18081	46.90039
2.83866	40.83075	2.24910	50.31773	2.10499	183.43300	1.50048	46.09043	.12054	46.89403
2.68360	41.95748	2.23640	75.52763	2.09960	183.36605	1.47349	46.36841	.06027	46.88315
2.52854	43.15583	2.22370	180.02574	2.09420	183.27707	1.44650	46.90363	0.00000	46.88315

KEQUV = .1007209E+00
 RESCOND= .6190376E-06
 RESSHLD= .1547446E-04
 HSC = 0.
 HSS = 0.
 MSI = 0.
 FOC = .3150826E+01
 FOS = .4546876E+00
 FOI = .1167897E-01
 FOO = .5275178E-03
 FOE = .2844686E-04

LOCAL TEMPERATURE DEGREES CENTIGRADE TIME IS .423E+01 SEC

EARTH		JACKET		SHIELD		INSULATOR		CONDUCTOR	
RADIUS	TEMP	RADIUS	TEMP	RADIUS	TEMP	RADIUS	TEMP	RADIUS	TEMP
6.25000	25.00000	2.52854	43.27012	2.22370	64.21199	2.09420	64.26818	1.44650	47.06900
6.09494	25.50433	2.51584	43.34158	2.21830	64.21535	2.06721	64.40162	1.38623	47.06611
5.93988	26.02126	2.50314	43.42480	2.21291	64.21864	2.04023	64.39472	1.32596	47.06333
5.78482	26.55186	2.49043	43.52455	2.20751	64.22183	2.01324	64.24975	1.26569	47.06065
5.62976	27.09687	2.47773	43.64715	2.20212	64.22434	1.98625	63.97137	1.20542	47.05806
5.47472	27.65712	2.46503	43.80097	2.19672	64.22797	1.95926	63.56882	1.14515	47.05557
5.31963	28.23346	2.45233	43.99697	2.19132	64.23091	1.93228	63.05066	1.08488	47.05318
5.16457	28.82685	2.43963	44.24910	2.18593	64.23377	1.90529	62.42930	1.02460	47.05080
5.00951	29.43834	2.42693	44.57454	2.18053	64.23653	1.87830	61.71805	.96433	47.04866
4.85445	30.06906	2.41422	44.99306	2.17514	64.23921	1.85131	60.93106	.90406	47.04653
4.69939	30.72026	2.40152	45.52941	2.16974	64.24180	1.82433	60.08283	.84379	47.04448
4.54433	31.39332	2.38882	46.20612	2.16435	64.24430	1.79734	59.18765	.78352	47.04250
4.38927	32.08975	2.37612	47.04744	2.15895	64.24671	1.77035	58.25912	.72325	47.04059
4.23421	32.81124	2.36342	48.07346	2.15355	64.24902	1.74336	57.30969	.66298	47.03873
4.07915	33.55965	2.35072	49.29697	2.14815	64.25125	1.71638	56.35027	.60271	47.03693
3.92409	34.33708	2.33802	50.71933	2.14276	64.25338	1.68939	55.38988	.54244	47.03516
3.76903	35.14587	2.32531	52.32631	2.13737	64.25542	1.66240	54.43544	.48217	47.03341
3.61397	35.98865	2.31261	54.08403	2.13197	64.25736	1.63541	53.49155	.42190	47.03165
3.45891	36.86841	2.29991	55.94016	2.12658	64.25921	1.60843	52.56044	.36163	47.02984
3.30384	37.79854	2.28721	57.81847	2.12118	64.26095	1.58144	51.64137	.30135	47.02794
3.14878	38.75293	2.27451	59.82041	2.11578	64.26260	1.55445	50.73325	.24108	47.02585
2.99372	39.76605	2.26181	61.26873	2.11039	64.26415	1.52746	49.82966	.18081	47.02340
2.83866	40.83314	2.24910	62.63737	2.10499	64.26560	1.50048	48.92404	.12054	47.02022
2.68360	41.96295	2.23640	63.64225	2.09960	64.26694	1.47349	48.00740	.06027	47.01519
2.52854	43.27012	2.22370	64.21199	2.09420	64.26818	1.44650	47.06900	0.00000	47.01519

DIELOS= .9039356E-02
 RESCOND= .6193142E-06
 RESSHLD= .1107195E-04
 HSC = .3619182E+00
 HSS = .8302867E+04
 HSI = .7605387E-01
 FOC = .1369358E+00
 FOS = .1093983E-02
 FOI = .5060889E-03
 FOO = .2285910E-04
 FOE = .1232697E-05

LOCAL TEMPERATURE DEGREES CENTIGRADE

TIME IS .163E+00 SEC

EARTH		JACKET		SHIELD		INSULATOR		CONDUCTOR	
RADIUS	TEMP	RADIUS	TEMP	RADIUS	TEMP	RADIUS	TEMP	RADIUS	TEMP
6.25000	25.00000	2.52854	43.27734	2.22370	262.14761	2.09420	282.55524	1.44650	48.34635
6.09494	25.50435	2.51584	43.35235	2.21830	264.62172	2.06721	178.38963	1.38623	48.34583
5.93388	26.02128	2.50314	43.44012	2.21291	266.93721	2.04023	119.27102	1.32596	48.34517
5.78482	26.55188	2.49043	43.54582	2.20751	269.09770	2.01324	88.58260	1.26569	48.34437
5.52976	27.09690	2.47773	43.67622	2.20212	271.10663	1.98625	73.87731	1.20542	48.34344
5.47470	27.65714	2.46503	43.84012	2.19672	272.96728	1.95926	67.22183	1.14515	48.34239
5.31963	28.23348	2.45233	44.04878	2.19132	274.68275	1.93228	64.21462	1.08488	48.34121
5.16457	28.82688	2.43963	44.31630	2.18593	276.25592	1.90529	62.69125	1.02460	48.33991
5.00951	29.43837	2.42693	44.65968	2.18053	277.68944	1.87830	61.69622	.96433	48.33849
4.85445	30.06909	2.41422	45.09863	2.17514	278.98571	1.85131	60.84909	.90406	48.33693
4.69939	30.72030	2.40152	45.65488	2.16974	280.14686	1.82433	60.01532	.84379	48.33524
4.54433	31.39336	2.38882	46.35080	2.16435	281.17473	1.79734	59.15617	.78352	48.33341
4.38927	32.08979	2.37612	47.20738	2.15895	282.07083	1.77035	58.26695	.72325	48.33142
4.23421	32.81128	2.36342	48.24142	2.15355	282.83632	1.74336	57.35375	.66298	48.32924
4.07915	33.55970	2.35072	49.46212	2.14816	283.47202	1.71638	56.42501	.60271	48.32686
3.92409	34.33713	2.33802	50.86741	2.14276	283.97833	1.68939	55.48875	.54244	48.32422
3.76903	35.14593	2.32531	52.44050	2.13737	284.35526	1.66240	54.55158	.48217	48.32127
3.61397	35.98871	2.31261	54.14792	2.13197	284.60237	1.63541	53.61865	.42190	48.31794
3.45891	36.86848	2.29991	55.94376	2.12658	284.71874	1.60843	52.69421	.36163	48.31411
3.30384	37.78861	2.28721	57.80553	2.12118	284.70298	1.58144	51.78335	.30135	48.30959
3.14878	38.75301	2.27451	59.93348	2.11578	284.55316	1.55445	50.89567	.24108	48.30407
2.99372	39.76614	2.26181	63.76965	2.11039	284.26683	1.52746	50.05174	.18081	48.29699
2.83866	40.83325	2.24910	75.92913	2.10499	283.84093	1.50048	49.29244	.12054	48.28708
2.68360	41.96330	2.23640	120.45943	2.09960	283.27183	1.47349	48.68873	.06027	48.27059
2.52854	43.27734	2.22370	262.14761	2.09420	282.55524	1.44650	48.34635	0.00000	48.27059

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 RESSHLD= .1912522E-04
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 FOE = .7868291E-04

LOCAL TEMPERATURE DEGREES CENTIGRADE TIME IS .117E+02 SEC

EARTH		JACKET		SHIELD		INSULATOR		CONDUCTOR	
RADIUS	TEMP	RADIUS	TEMP	RADIUS	TEMP	RADIUS	TEMP	RADIUS	TEMP
6.25000	25.00000	2.52854	45.18021	2.22370	72.95179	2.09420	73.13506	1.44650	50.56754
6.09494	25.50539	2.51584	46.72147	2.21830	72.96271	2.06721	73.20702	1.38623	50.56157
5.93988	26.02250	2.50314	47.35091	2.21291	72.97337	2.04023	73.20006	1.32596	50.55570
5.78482	26.55318	2.49043	48.07222	2.20751	72.98376	2.01324	73.11099	1.26569	50.54993
5.62976	27.09829	2.47773	48.88869	2.20212	72.99388	1.98625	72.93704	1.20542	50.54424
5.47470	27.65862	2.46503	49.80288	2.19672	73.00373	1.95926	72.67581	1.14515	50.53864
5.31963	28.23507	2.45233	50.81616	2.19132	73.01330	1.93228	72.32530	1.08488	50.53311
5.16457	28.82858	2.43963	51.92929	2.18593	73.02259	1.90529	71.88391	1.02460	50.52764
5.00951	29.44019	2.42693	53.13697	2.18053	73.03161	1.87830	71.35045	.96433	50.52222
4.85445	30.07105	2.41422	54.43742	2.17514	73.04034	1.85131	70.72410	.90406	50.51682
4.69939	30.72240	2.40152	55.82203	2.16974	73.04878	1.82433	70.00440	.84379	50.51144
4.54433	31.39563	2.38882	57.28032	2.16435	73.05694	1.79734	69.19127	.78352	50.50603
4.38927	32.09225	2.37612	58.79733	2.15895	73.06480	1.77035	68.28493	.72325	50.50058
4.23421	32.81395	2.36342	60.35647	2.15355	73.07237	1.74336	67.28593	.66298	50.49504
4.07915	33.56260	2.35072	61.93667	2.14816	73.07964	1.71638	66.19512	.60271	50.48936
3.92409	34.34030	2.33802	63.51411	2.14276	73.08661	1.68939	65.01357	.54244	50.48368
3.76903	35.14939	2.32531	65.08234	2.13737	73.09327	1.66240	63.74262	.48217	50.47730
3.61397	35.99252	2.31261	66.55289	2.13197	73.09962	1.63541	62.38378	.42190	50.47069
3.45891	36.87267	2.29991	67.95604	2.12658	73.10566	1.60843	60.93876	.36163	50.46367
3.30384	37.79326	2.28721	69.24168	2.12118	73.11138	1.58144	59.40939	.30135	50.45535
3.14878	38.75819	2.27451	70.38029	2.11578	73.11678	1.55445	57.79762	.24108	50.44585
2.99372	39.77214	2.26181	71.34397	2.11039	73.12185	1.52746	56.10549	.18081	50.43406
2.83866	40.84583	2.24910	72.10749	2.10499	73.12659	1.50048	54.33506	.12054	50.41801
2.68360	42.11839	2.23640	72.64917	2.09960	73.13100	1.47349	52.48840	.06027	50.39170
2.52854	46.18021	2.22370	72.95179	2.09420	73.13506	1.44650	50.56754	0.00000	50.39178

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 FOC = .1489752E+06
 FOS = .1965673E-03
 FOI = .5521973E-03
 FOO = .2494174E-04
 FOE = .1345005E-05

LOCAL TEMPERATURE DEGREES CENTIGRADE TIME IS .200E+00 SEC

EARTH		JACKET		SHIELD		INSULATOR		CONDUCTOR	
RADIUS	TEMP	RADIUS	TEMP	RADIUS	TEMP	RADIUS	TEMP	RADIUS	TEMP
6.25000	25.00000	2.52854	46.25867	2.22370	251.74231	2.09420	302.93523	1.44650	51.93720
6.09494	25.50540	2.51584	46.80248	2.21833	264.59381	2.06721	194.33730	1.38623	51.93390
5.93988	26.02252	2.50314	47.43437	2.21291	275.66995	2.04023	132.40026	1.32596	51.93052
5.78482	26.55321	2.49043	48.15769	2.20751	285.13470	2.01324	99.92089	1.26569	51.92706
5.62976	27.09831	2.47773	48.97535	2.20212	293.14987	1.98625	84.16224	1.20542	51.92353
5.47470	27.65805	2.46503	49.88952	2.19672	299.87253	1.95926	76.97313	1.14515	51.91994
5.31963	28.23510	2.45233	50.90116	2.19132	305.45255	1.93228	73.76342	1.08488	51.91629
5.16457	28.82861	2.43963	52.06962	2.18593	310.03033	1.90529	72.22205	1.02460	51.91258
5.00951	29.44022	2.42693	53.21223	2.18053	313.73489	1.87830	71.29428	.96433	51.90882
4.85445	30.07108	2.41422	54.56388	2.17514	316.68218	1.85131	70.53853	.90406	51.90501
4.69939	30.72244	2.40152	55.87671	2.16974	318.97389	1.82433	69.78356	.84379	51.90113
4.54433	31.39567	2.38882	57.31983	2.16435	320.69654	1.79734	68.96747	.78352	51.89719
4.38927	32.09229	2.37612	58.81916	2.15895	321.92094	1.77035	68.06942	.72325	51.89318
4.23421	32.81399	2.36342	60.35734	2.15355	322.70203	1.74336	67.08314	.66298	51.88906
4.07915	33.56265	2.35072	61.91392	2.14816	323.07892	1.71638	66.00734	.60271	51.88483
3.92409	34.34035	2.33802	63.46553	2.14276	323.07520	1.68939	64.84255	.54244	51.88044
3.76903	35.14949	2.32531	64.98651	2.13737	322.69938	1.66240	63.59017	.48217	51.87582
3.61397	35.99258	2.31261	66.45024	2.13197	321.94558	1.63541	62.25246	.42190	51.87091
3.45891	36.87274	2.29991	67.83554	2.12658	320.79419	1.60843	60.83334	.36163	51.86557
3.30384	37.79334	2.29721	69.16284	2.12118	319.21274	1.58144	59.34019	.30135	51.85959
3.14878	38.75827	2.27451	70.68949	2.11578	317.15679	1.55445	57.78767	.24108	51.85265
2.99372	39.77224	2.26181	73.83242	2.11039	314.57089	1.52746	56.20408	.18081	51.84410
2.83866	40.84624	2.24910	84.75897	2.10499	311.38958	1.50048	54.64028	.12054	51.83254
2.68360	42.12450	2.23640	125.02671	2.09960	307.53947	1.47349	53.17869	.06027	51.81371
2.52854	46.25867	2.22370	251.74231	2.09420	302.93523	1.44650	51.93720	0.00000	51.81371

CHAPTER IV

RESULTS

The computer program has been used to predict both steady state and transient temperature distributions in underground cables. Typical results are shown in Figures 6 through 15. The steady state results are plotted in Figures 6 through 12 and the results are compared with available ampacity tables [12] in Figures 11 and 12. The transient results are given in Figures 13 through 15 and they are compared with the results of Martin and Reczek [4].

Figure 6 shows the local temperature in a typical 1 million circular mil cable for the center cable in a flat three cable arrangement. The cables are buried at a depth of 122 cm. Currents vary from 400 to 600 amps and the voltage is a constant 25,000 volts, phase to phase which is equivalent to 14,434 volts phase to neutral. The temperature level increases with current but even at 600 amps the conductor temperature is below 90°C which is a safe level for typical cable materials. A current of 400 amps produces a conductor temperature of slightly over 50°C. The conductor is the hottest portion of the cable and the temperature drops gradually as the distance from the center increases. The high thermal conductivity of the conductor and shield makes these areas almost isothermal. For all three current levels, the ambient soil temperature is 25°C, so the total temperature rise for each current level is approximately 27°C, 42°C and 61°C for 400, 500 and 600 amps,

respectively.

Figure 7 shows the effect of depth on the central conductor temperature for three current levels. The cable geometry and cable materials are identical for those for Figure 6. As expected, the conductor temperature increases with current and it is less sensitive to the depth of burial. For example, for a current of 500 amps, the conductor temperature increases only about 5°C as the depth is increased from 90 cm to 150 cm.

Figure 8 shows the effect of cable spacing on the conductor temperature for three different current levels. The conductor temperature increases only about 5°C at 700 amps for the range of cable spacing given in the figure. The conductor temperature increased as spacing between the cable increases because of increased circulating currents in the shield.

For a 1 million circular mil conductor, Figure 9 illustrates the effect of cable voltage on the conductor temperature. Since the cable heating is independent of voltage except for the dielectric loss, the conductor temperature remains relatively unaffected by the voltage. This curve shows how little the dielectric losses affect the overall cable temperature and how the I^2R losses in the conductor and shield dominate the heat generation in the cable.

For the same cable system as in Figures 6, 7 and 8, Figure 10 shows the effect of shield construction on cable temperature. The wire shield produces slightly higher temperatures at currents above 400 amps, but the increase is small. The wire shield produces higher conductor temperatures because the air gaps between shield wires cause a lower

1 million circular mil conductor
 Solid shield, insulation (XLP), Jacket (PVC)
 Insulation thickness - 0.6477 cm
 Voltage - 14,434 volt (phase to neutral)
 3 cables horizontally on 20.32 cm center, 122 cm deep

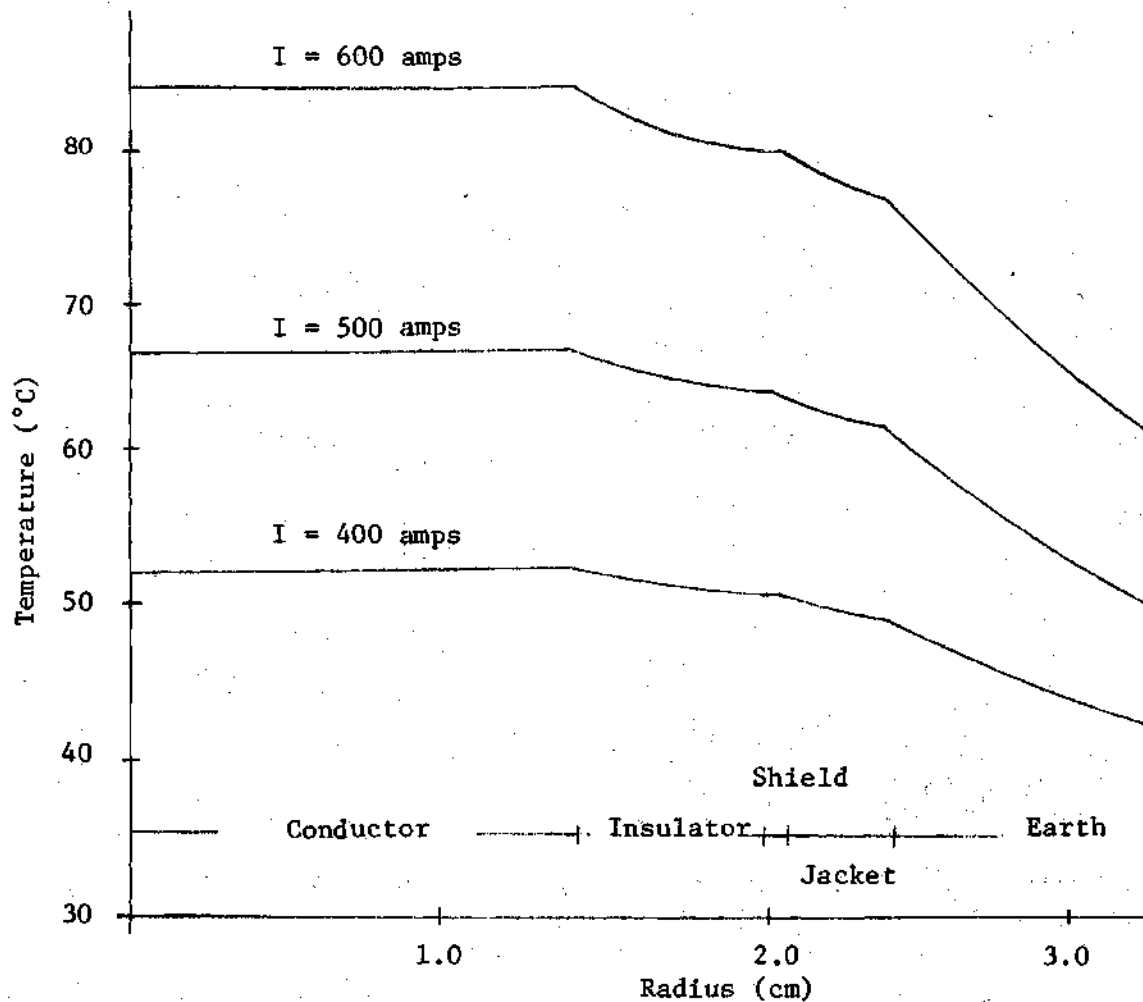


Figure 6. Steady State Radial Temperature Distribution As A Function Of Conductor Current.

1 million circular mil conductor
Wire shield (21 #10)
Insulation (XCP) Jacket (PVC)
Insulation thickness - 0.6477 cm
Voltage - 14434 volt (phase to neutral)
3 cables horizontally on 20.32 cm center

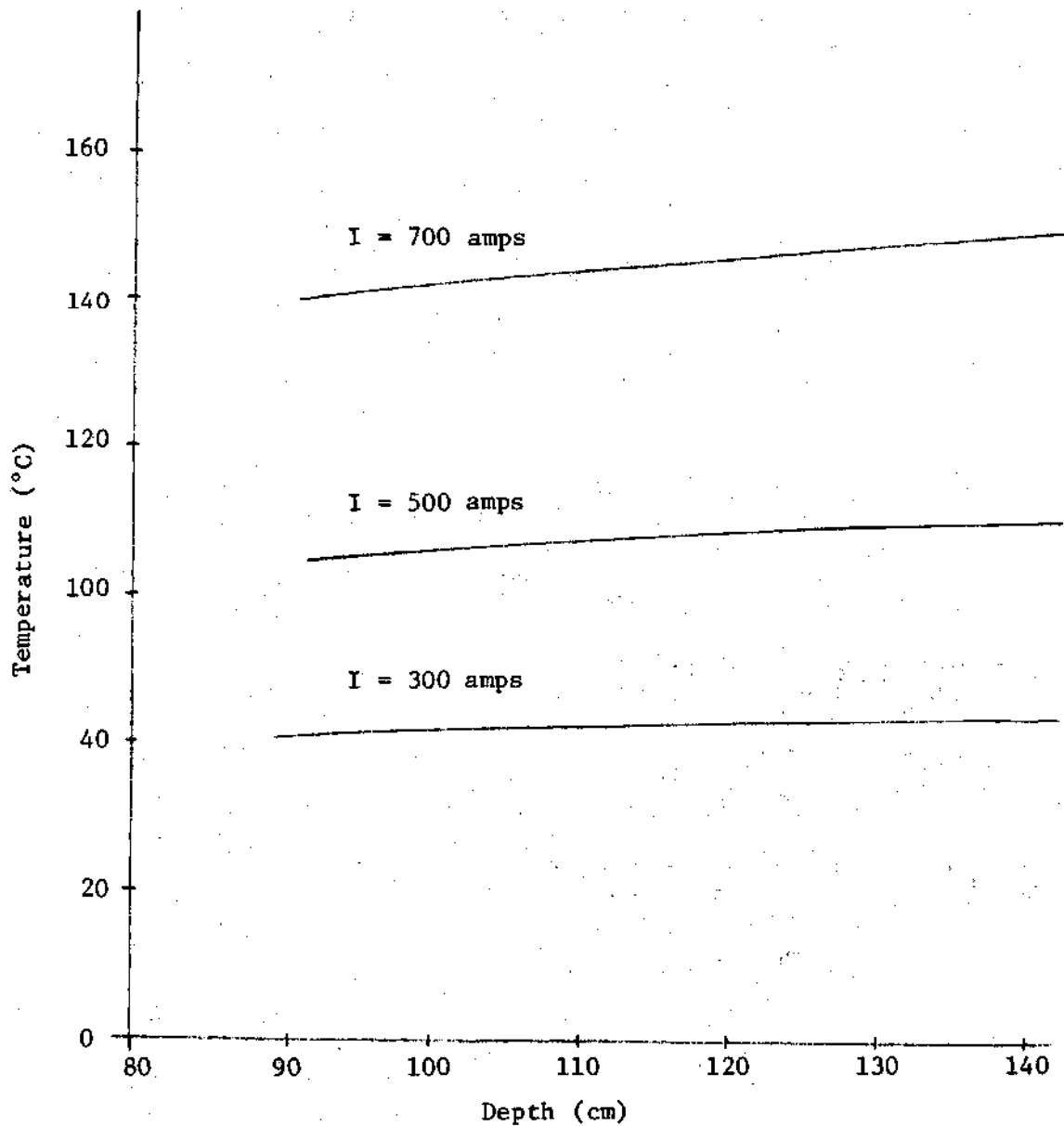


Figure 7. Steady State Conductor Temperature As A Function Of Cable Depth And Current.

1 million circular mil conductor
Wire Shield (21 #10)
Insulation (XLP) Jacket (PVC)
Insulation thickness - 0.6477 cm
Voltage - 14,434 volt (phase to neutral)
3 cable horizontally buried 122.0 cm deep

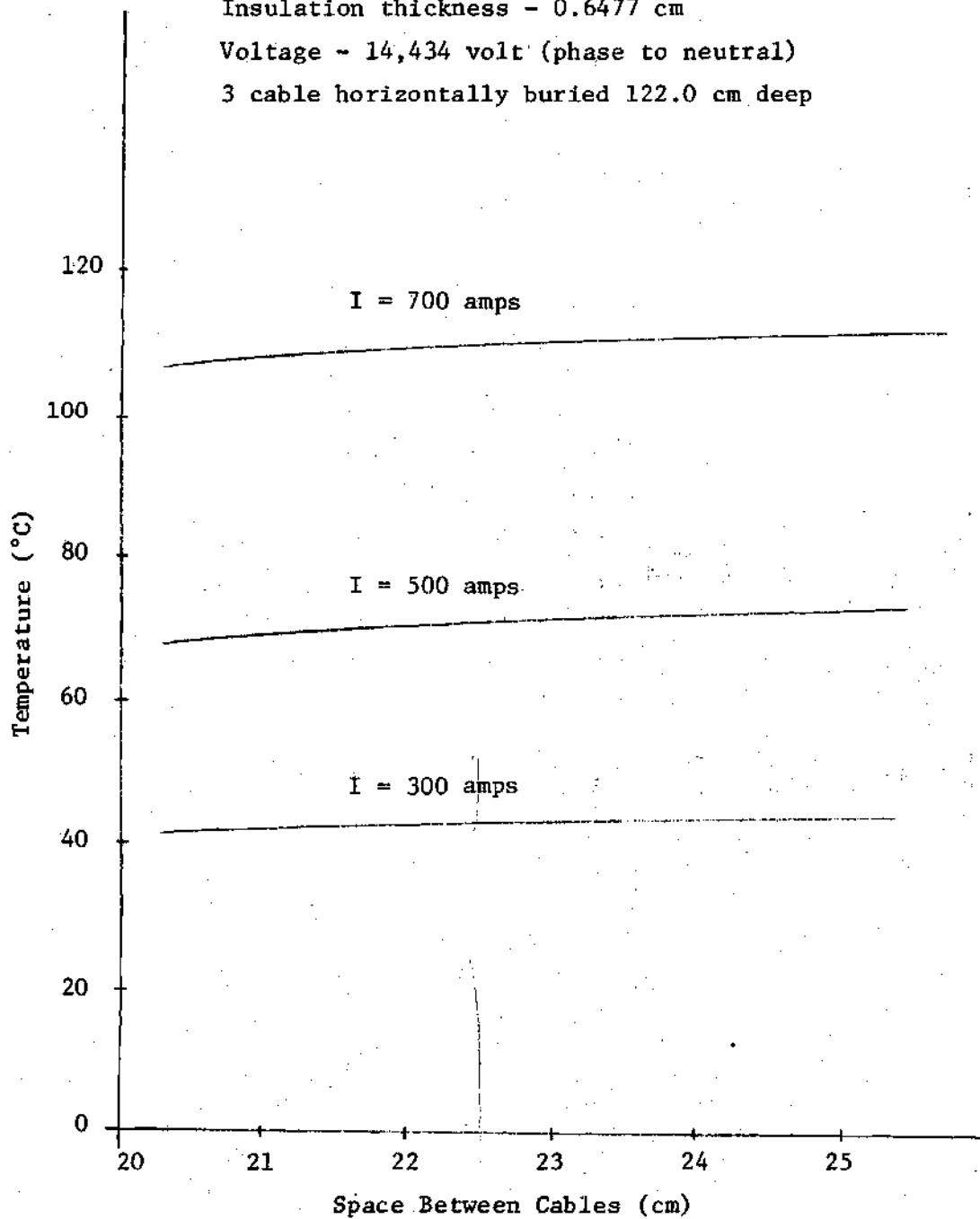


Figure 8. Steady State Conductor Temperature As A Function Of Spacing Between Cables And Current.

1 million circular mil conductor
Wire shield (21 #10)
Insulation (XLP) Jacket (PVC)
Insulation thickness - 0.6477 cm
3 cables horizontally on 20.32 center 122.0 deep

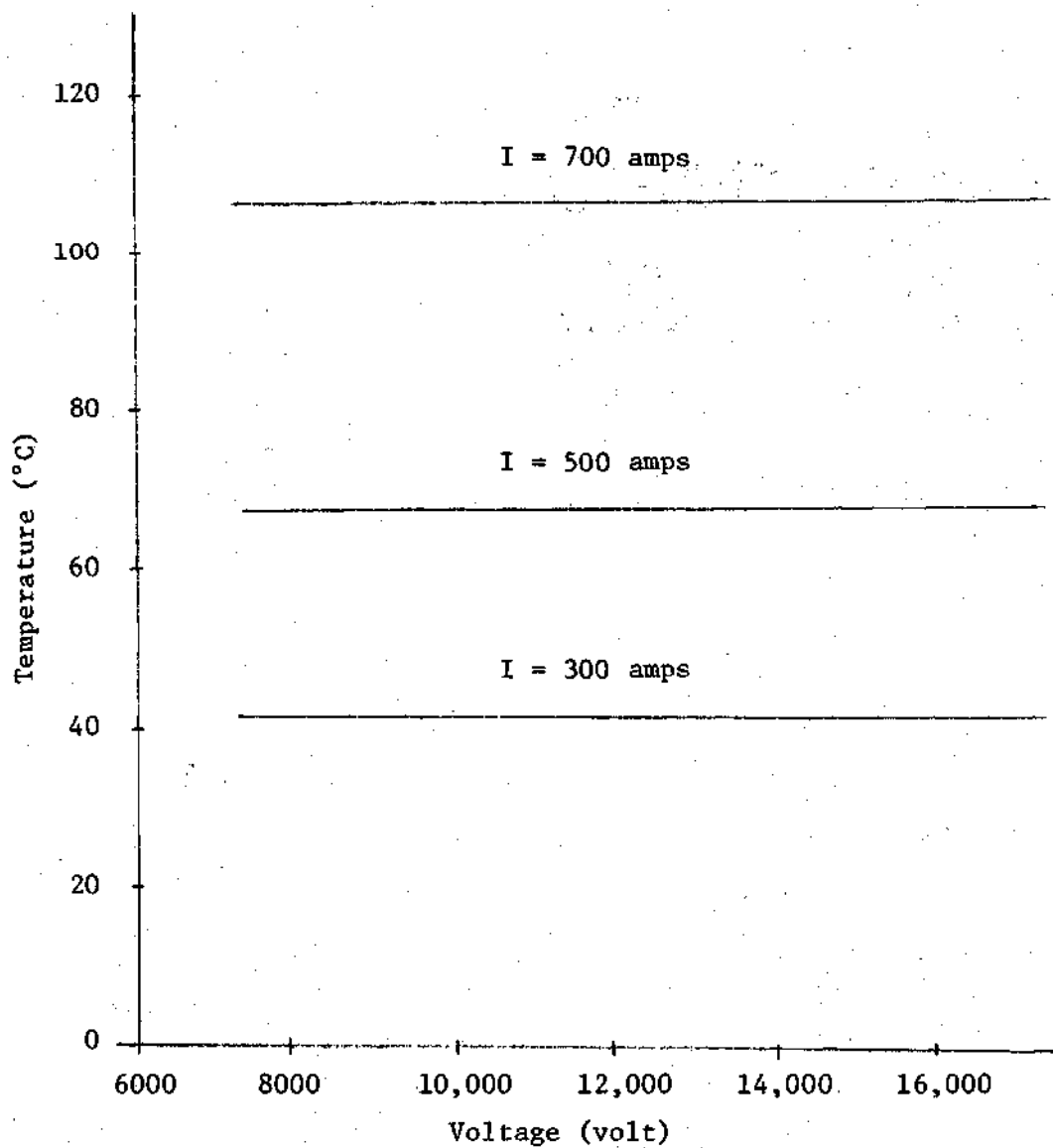


Figure 9. Steady State Conductor Temperature As A Function Of Phase To Neutral Voltage And Current.

1 million circular mil conductor
Wire shield (21 #10) and solid shield (copper)
Insulation (XLP) Jacket (PVC)
Insulation Thickness - 0.6477 cm
Voltage - 14.434 volt (phase to neutral)
3 cables horizontally on 20.32 cm center
122.0 cm deep

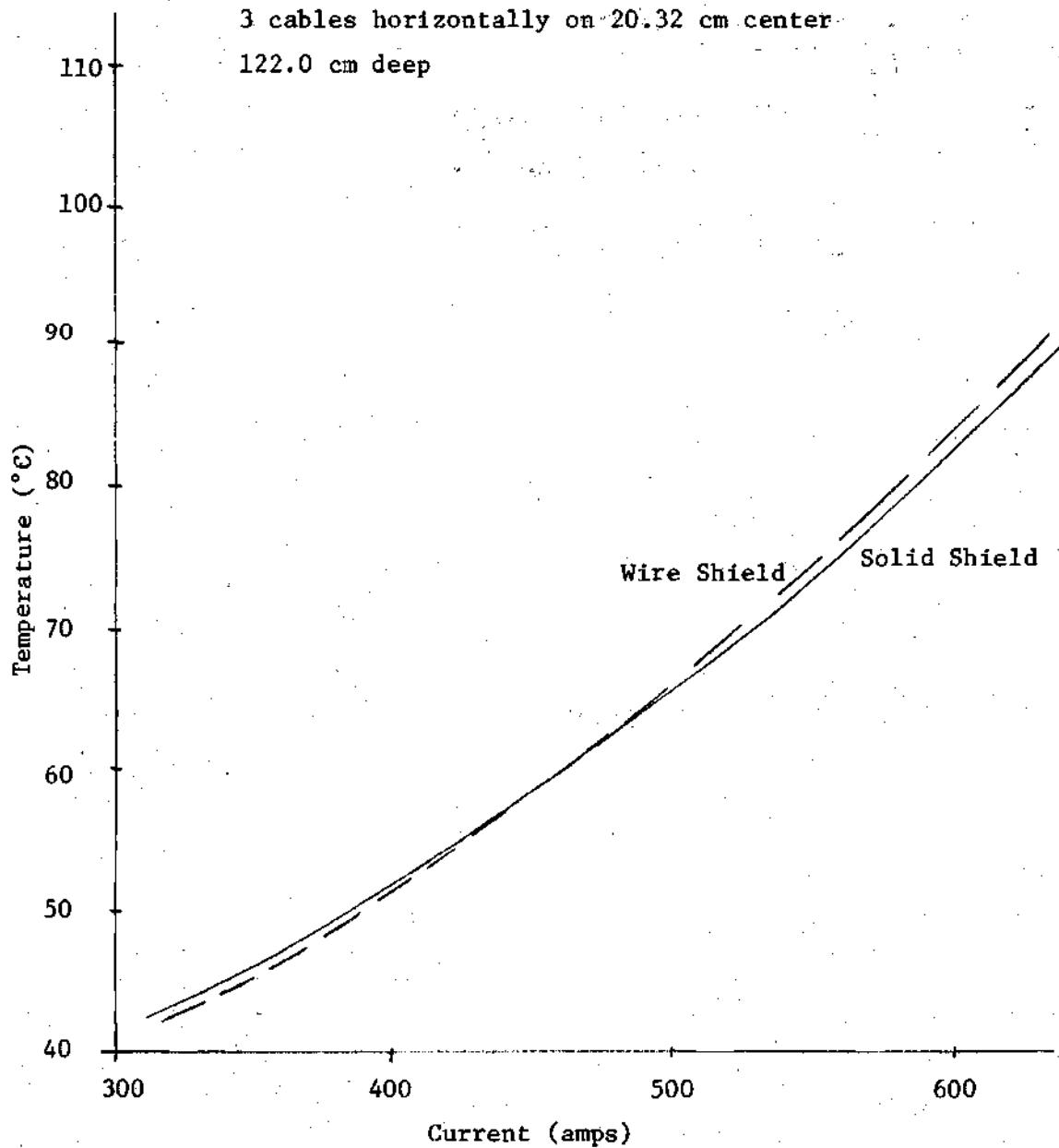


Figure 10. The Effect Of Shield Constructions On Steady State Conductor Temperature.

shield thermal conductivity.

The cable conditions used in Figure 11 were selected to coincide with those given in the IPCEA-NEMA ampacity tables [12]. The cable is a 1 million circular mil conductor with XLP insulation and wire shield with no jacket. The three cables are buried at a depth of 91.44 cm and spaced on 19.05 cm centers. Two cases of different diameter shield wires are selected for comparison. The computer results compare favorably with the ampacity tables with the maximum temperature difference between the two of about 8°C.

Figure 12 compares the steady state 1 million circular mil conductor temperature predicted by the computer program with one supplied by Georgia Power Company for similar conditions. The maximum difference in temperature is 5°C. The Georgia Power program is based on the theory of Neher and McGrath [1].

The remaining figures in this section illustrate the program results for transient cable behavior. The type of transient is one expected to occur when a fault in the circuit is detected. Under fault conditions the current is suddenly increased from a steady state value to a fault level. The fault current is conducted through the conductor, through the fault location, and into the shield. The fault current level continues until automatic switching devices detect the fault and open the circuit causing the current level to drop to zero. The switch continues to open and close the circuit assuming that the reason for the fault will correct itself. If the fault does not disappear, the circuit will remain open after several attempts to reclose.

Figure 13 shows the shield temperature when the circuit is faulted

1 million circular mil conductor
 Wire shield, insulation (XLP), no jacket
 Insulation thickness - 0.66043 cm
 Voltage - 15000 volt (phase to neutral)
 3 cables horizontally on 19.05 cm center
 91.44 deep

--- computer output
 — reference [12]

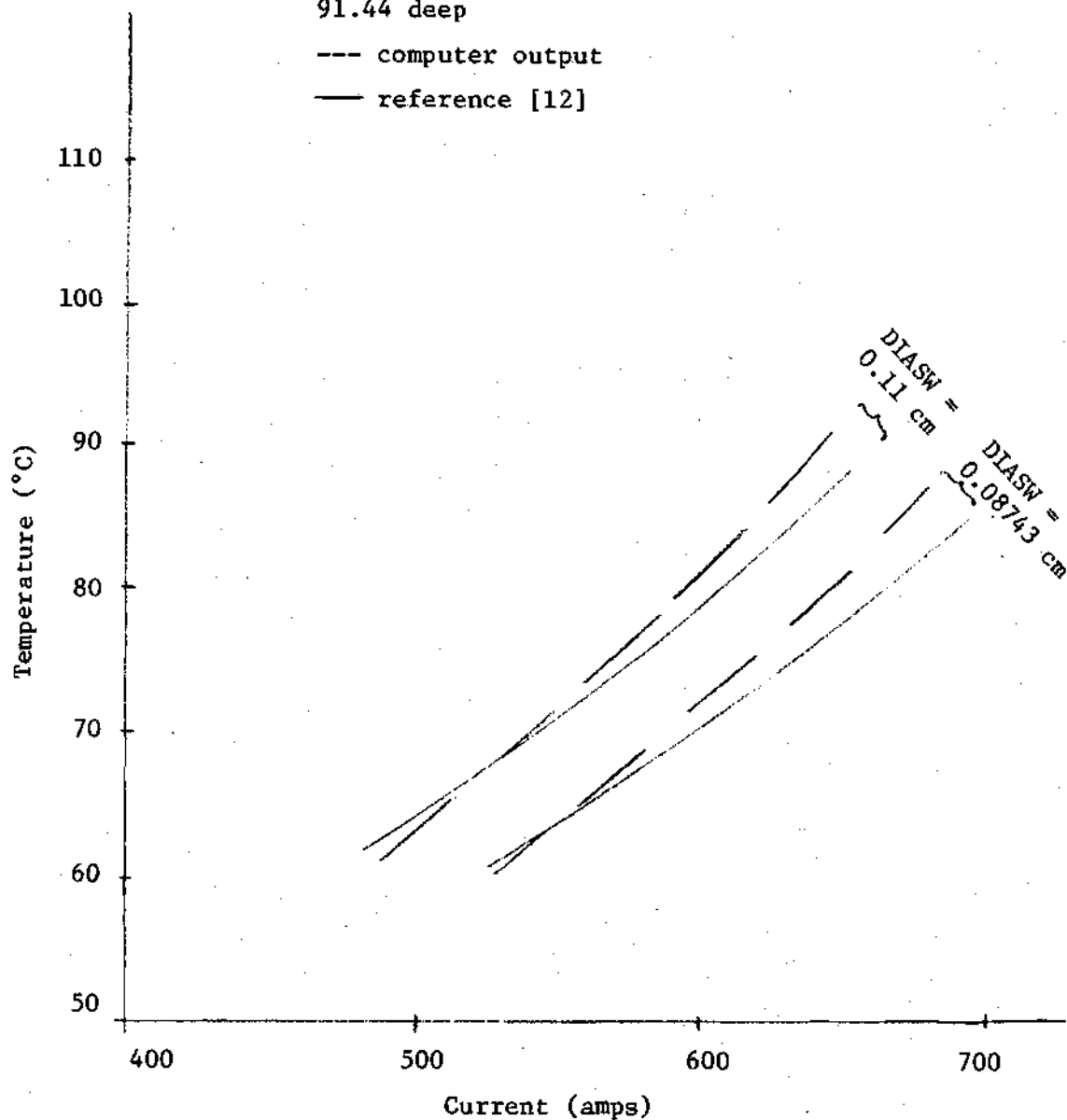


Figure 11. Comparison Of Computer Output With Ampacity Table [12] For Steady State Temperature.

1 million circular mil conductor, wire
shield (21 #10)

Insulation (XLP) Jacket (PVC)

Insulation thickness - 0.6477 cm

Voltage - 14.434 volt (phase to neutral)

3 cables horizontally on 20.32 cm center, 122.0
cm deep

--- computer output

— reference [16]

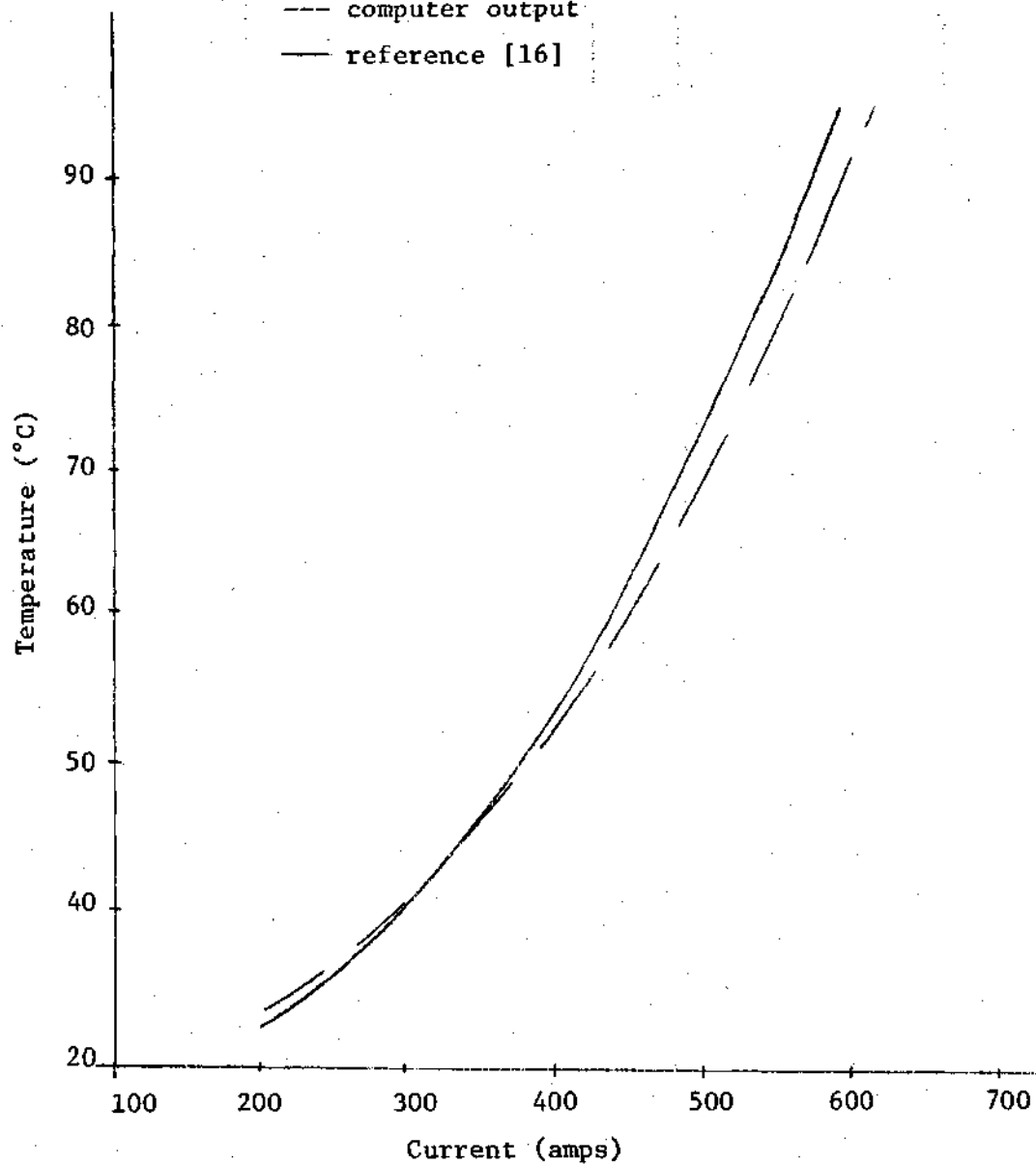


Figure 12. Comparison Of Computer Output
and Reference [16] For Steady State Temperature.

through three cycles. The fault current is assumed to be 9760 amps. The on-off times are typical of those experiences with circuit breakers used in the field. The results show reasonable comparison between the computer output and the experimental results of Martin and Reczek [4]. The shield temperatures are plotted because they are the highest temperatures in the cable during a transient condition. The shield resistance is on the order of three times that of the conductor so that even though the same current passes through both the shield and conductor, the temperature rise in the shield is greater. Furthermore, there is less mass in the shield so it is less able to store the energy in the shield material.

The program predicts the abrupt shield temperature rise during the time that the fault current is passed through the shield and conductor. The data also show the gradual decrease in shield temperature when the circuit is open and the current drops to zero. During this time the heat from the shield and conductor is conducted into the adjacent insulation materials thereby reducing the shield and conductor temperatures. The maximum shield temperature at the end of each "on" cycle begins to increase but remains about constant between the second and third short circuit cycle. This is primarily due to the relatively long time that the circuit remains open (about 10 sec) during this time thereby allowing the heat to be conducted into the insulation.

The computer program predicts temperature rises which are initially larger and eventually smaller than those predicted by a program developed at Georgia Power Company. The Georgia Power Company program is based on work by Mildner et al. [17] which assumes that the heat flows

1 million circular mil conductor
Wire shield (19 #14)
Insulation Thickness 0.6477 cm
Voltage - 14,434 volt (phase to neutral)
3 cables horizontally on 20.32 cm center, 122 cm deep
Fault current - 9760 amps
Fault sequence - 0.3416 sec on, 3.2 sec off, 0.416 sec on
9.7 sec off, 0.3416 sec on

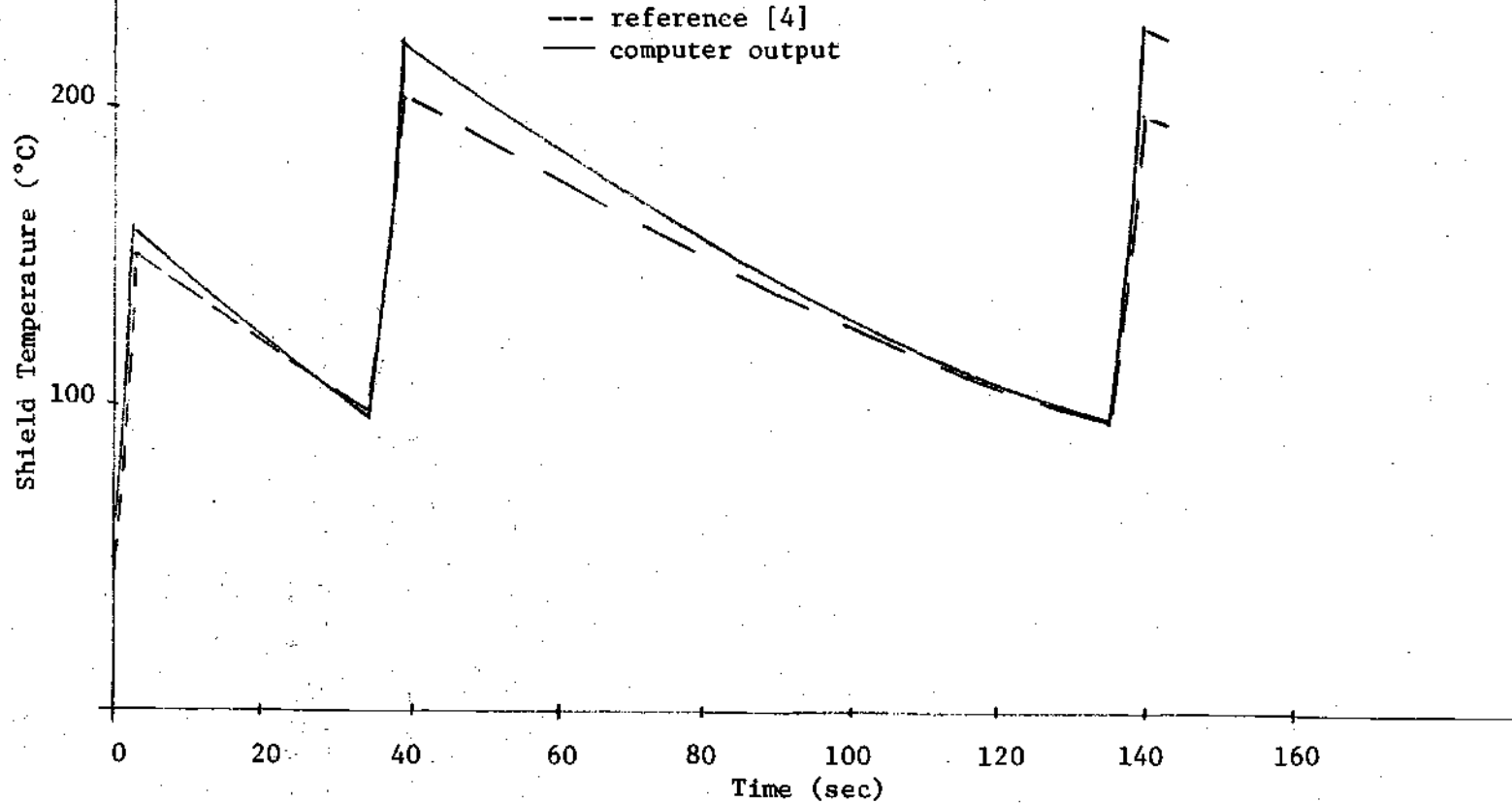


Figure 13. Comparison Between Output And Reference [4]
For Fault Conditions I.

1 million circular mil conductor
Wire shield (14 #16 AWG)
Insulation (XLP) Jacket (SCP)
Insulation thickness - 0.6477 cm
Voltage - 14,434 volts (phase to neutral)
3 cables horizontally on 20.32 cm center, 122 cm deep
Fault current - 8394 amps
Fault sequence - 0.128 sec on, 4.23 sec off, 0.183 sec on
11.7 sec off, 0.2 sec on

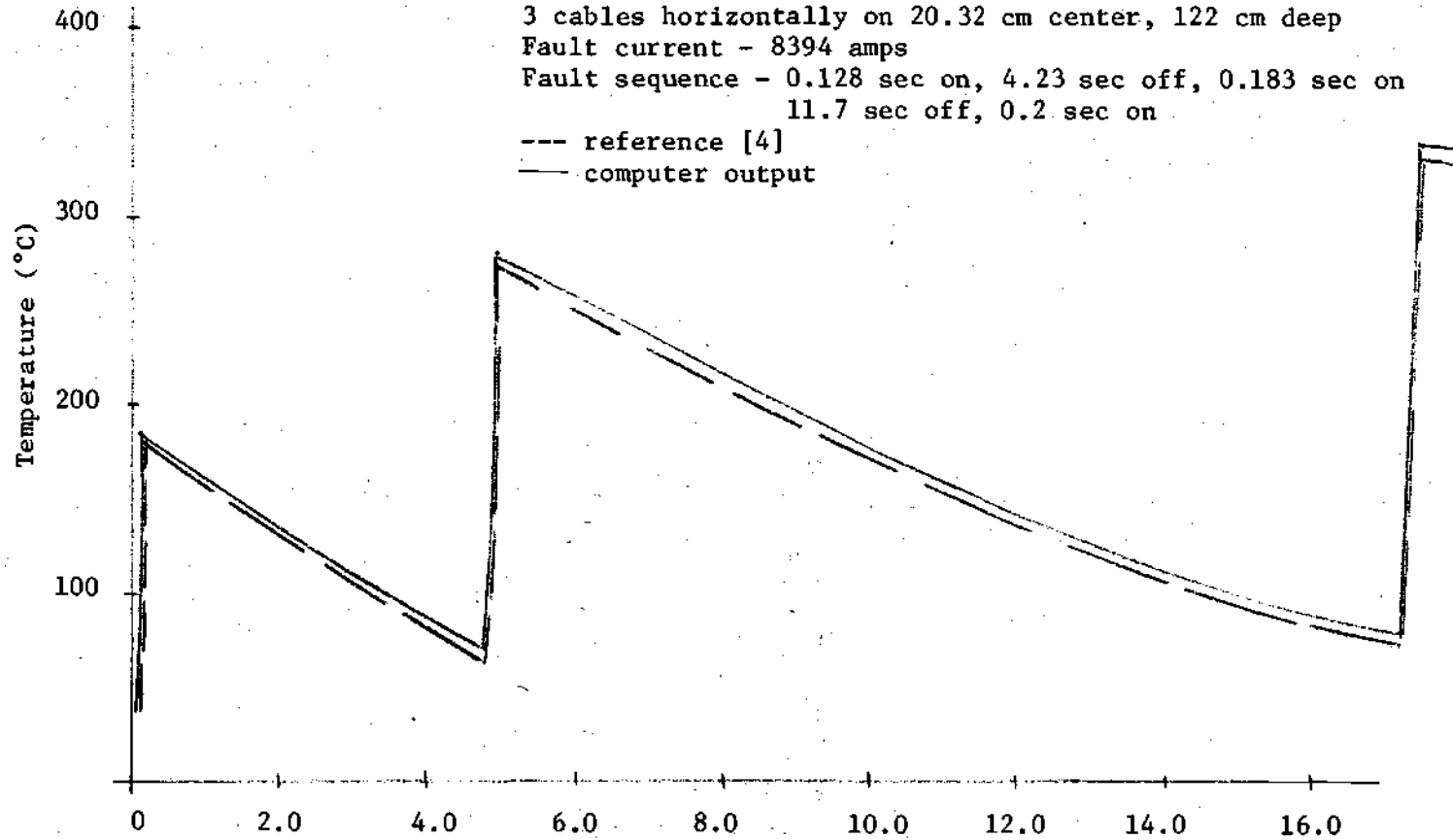


Figure 14. Comparison Between Output And Reference [4] For Fault Condition II.

from only one side of the shield and it is insulated on the other side. The program described in this thesis allows heat to flow to both sides of the shield. When heat flows from the shield into the jacket and insulation, the resulting temperature rise of the shield is eventually lower than that predicted by the model of Mildner.

The results in Figure 14 are similar to those of Figure 13 but they represent cable behavior for a slightly different cable geometry. The shield construction is slightly different, and the fault current is higher. The transient shield temperature is again compared with the experimental work conducted by Georgia Power Company. The program predicts temperatures which are initially higher and eventually lower than measured values, although the differences are limited to about 15°C.

Local, transient temperatures are illustrated in Figure 15. The temperature levels show how the cable heats up locally at the end and beginning of each short circuit cycle. The cable temperature is initially at a temperature labeled as steady state. The temperature distribution at the end of the first short circuit cycle is marked as ON-1. At this time the conductor temperature has increased to about 53°C and the shield temperature has increased to about 114°C, which is the highest temperature in the cable at that time.

The temperatures in the cable that exist after the circuit has been open for the first time are labeled as OFF-1. The conductor temperature increases less than 1°C during the open circuit period, while the shield decreases about 70°C. The heat generated in the shield and conductor during the fault has been conducted into the adjacent insulation and into the earth. During the short circuit, the insulation has a

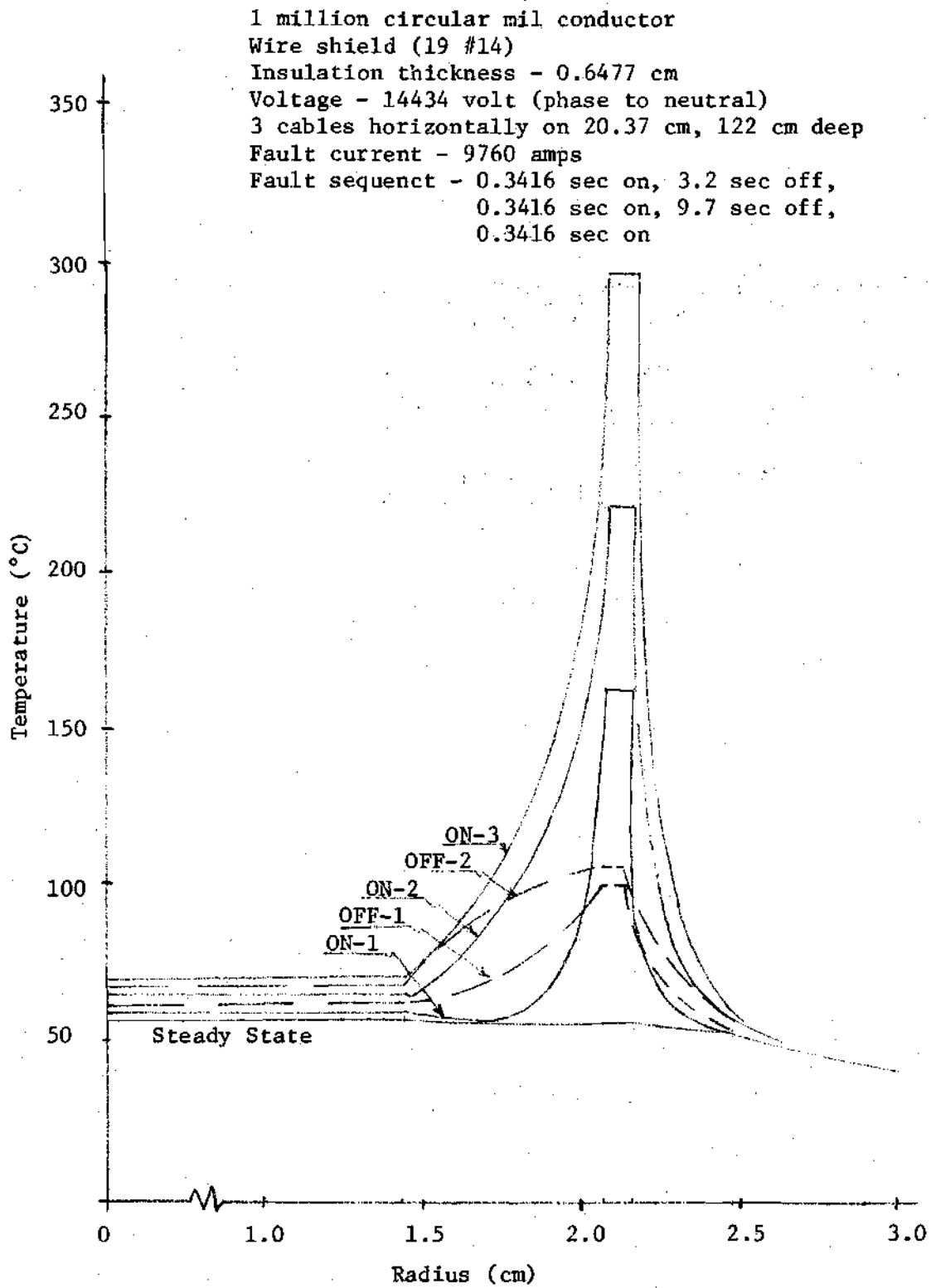


Figure 15. Local Temperature At The End
 Of Each Short-Circuit Cycle.

minimum temperature near its center. But after the end of the first open circuit, the heat generated by the shield and conductor has had time to be conducted toward that location and the minimum temperature is eliminated.

The behavior of the cable during the second and third cycle is similar to the first cycle. The maximum temperature exists in the shield material after the end of each fault period. The shield reaches a temperature of 225°C at the end of the second fault and it has cooled to 105°C after the circuit is open for about 10 seconds. The heat generated in the conductor has had enough time during that period to raise the conductor temperature by approximately 2°C. Under these conditions, the temperature levels of the conductor are low enough to prevent serious cable damage in that region. But the shield temperature is high enough to melt or seriously degrade the insulation and jacket material.

CHAPTER V

CONCLUSIONS

The computer program and analysis presented in this thesis can have a significant economic impact on the design and current rating of underground power cables. The program can predict operating temperatures for steady state and transient conditions. It, therefore, is a versatile design tool for one who has the responsibility of selecting cable materials and current levels which will result in safe operating temperatures. With such information, cables can be loaded to maximum current levels without risking damage to the cable insulation. Also, fault detection equipment can be designed to maintain an open circuit until the cable temperature has decreased to a safe level before attempting to reclose the circuit.

Initial program output has indicated that the conductor temperature during a typical fault sequence remains within a safe level after three reclosures. However, the shield reaches potentially damaging temperatures after the second reclosure. After the third reclosure, the shield temperature can easily exceed 200°C. This situation can be corrected by increasing the time interval that the circuit is left open. Both steady and transient results show reasonable comparison with existing data from available literature.

APPENDIX A

EQUIVALENT SHIELD THERMAL CONDUCTIVITY

The thermal conductivity of a wire shield consists of copper and air. If we let p = percent area of contact between shield wire and surrounding insulation where:

= 1.0 implies wire contacts insulation over the complete surface area.

= 0.0 implies point contact.

Total contact between the wire and insulation would imply contact over an arc of D_s , the percent contact would be given by

$$p = \frac{2\phi (D_s/2)}{\pi D_s} = \frac{\phi}{\pi} \quad (\phi \text{ in radius})$$

where ϕ is the angle of contact shown in Figure 15

then

$$r_i \psi = \frac{D_s}{2} \phi$$

or

$$\psi = \frac{D_s}{2r_i} \phi$$

If the round wire is replaced by an equivalent mass but with a

segment of a hollow cylinder as shown in Figure 15 then the resistance of the shield wire becomes

$$R_s = \frac{(2\pi/\psi)}{2\pi K_s} \ln \frac{r_o}{r_i}$$

and the air resistance becomes

$$R_A = \frac{(2\pi/\phi)}{2\pi K_A} \ln \frac{r_o}{r_i}$$

the total resistance of the shield is given by

$$\frac{1}{R_{\text{total}}} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_{n_s}} \right)_{\text{copper}} + \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_{n_s}} \right)_{\text{air}}$$

$$= \frac{N_s}{R_{\text{copper}}} + \frac{N_s}{R_{\text{air}}} = N_s \left[\frac{1}{R_{\text{copper}}} + \frac{1}{R_{\text{air}}} \right]$$

$$\therefore \frac{2\pi K_{\text{total}}}{\ln \frac{r_o}{r_i}} = \frac{N_s [K_{\text{copper}} \psi + K_{\text{air}} \theta]}{\ln \frac{r_o}{r_i}}$$

or

$$K_{\text{total}} = \frac{N_s}{2\pi} [K_{\text{copper}} \psi + K_{\text{air}} \theta]$$

where

$$\psi = \frac{D_s \phi}{2r_i}$$

$$\phi = \pi p$$

$$\theta = \frac{(2\pi - N_s \phi)}{N_s}$$

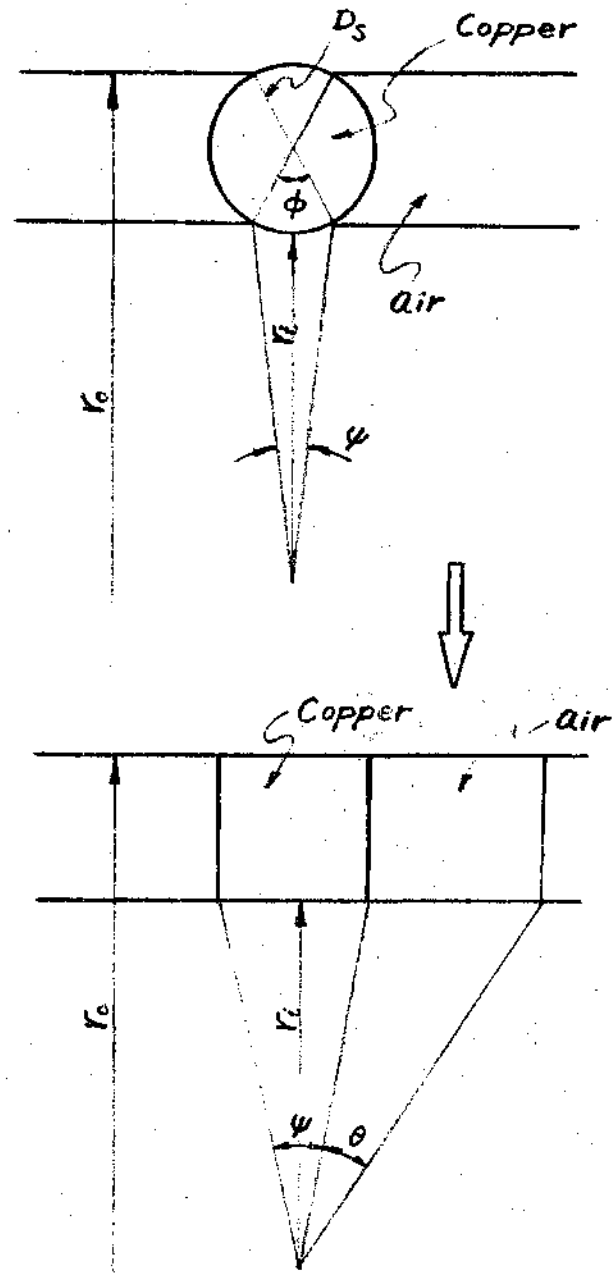


Figure 16. The Contact Between Wire And Insulation.

APPENDIX B

MUTUAL HEATING EFFECTS

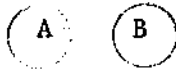
The mutual heating effects between the several cables that may be buried in the earth are accounted for by an imaging technique. The buried cable is reflected in a plane which corresponds to the surface of the earth. The technique follows an analysis by Kennelly [13]. The application of this work to the present problem of buried cables is outlined in reference [1] and it results in the factor F given in equation (II.C. 4). The expression for F is

$$F = \frac{d_{12}'}{d_{12}} \cdot \frac{d_{13}'}{d_{13}} \cdots \frac{d_{1n}'}{d_{1n}} \quad (1)$$

The symbol d_{ij}' is the distance between cable i and the image of cable j reflected in the plane of the surface of the earth. The symbol d_{ij} is the distance between the two cables i and j . The factor F depends upon which cable is assumed to be the reference cable for temperature calculations. Equation (1) is written as if cable 1 is the reference cable. The equation consists of $n - 1$ terms where n is the number of cables considered.

There are six possible cable arrangements considered in this thesis. The various distances d_{ij} and d_{ij}' are given on the following pages for these six cable arrangements.

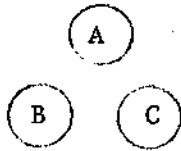
1. One phase



$$d_{12'} = \sqrt{s^2 + (2d)^2}$$

$$d_{21'} = \sqrt{s^2 + (2d)^2}$$

2. Equilateral



$$d_{12'} = \sqrt{\left(\frac{1}{2}s\right)^2 + \left(2d + \frac{\sqrt{3}}{2}s\right)^2}$$

$$d_{13'} = \sqrt{\left(\frac{1}{2}s\right)^2 + \left(2d + \frac{\sqrt{3}}{2}s\right)^2}$$

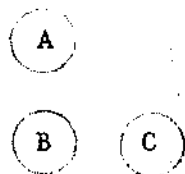
$$d_{21'} = \sqrt{\left(\frac{1}{2}s\right)^2 + \left(2d + \frac{\sqrt{3}}{2}s\right)^2}$$

$$d_{23'} = \sqrt{(s)^2 + (2d + \sqrt{3}s)^2}$$

$$d_{31'} = \sqrt{\left(\frac{1}{2}s\right)^2 + \left(2d + \frac{\sqrt{3}}{2}s\right)^2}$$

$$d_{32'} = \sqrt{(s)^2 + (2d + \sqrt{3}s)^2}$$

3. Right Triangular



$$d_{12}' = 2d + s$$

$$d_{13}' = \sqrt{(2d + s)^2 + (s)^2}$$

$$d_{21}' = 2d + s$$

$$d_{23}' = \sqrt{(2d + 2s)^2 + s^2}$$

$$d_{31}' = \sqrt{(2d + s)^2 + s^2}$$

$$d_{32}' = \sqrt{(2d + 2s)^2 + s^2}$$

4. Flat



$$d_{12}' = \sqrt{(2d)^2 + s^2}$$

$$d_{13}' = \sqrt{(2d)^2 + (2s)^2}$$

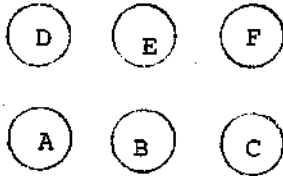
$$d_{21}' = \sqrt{(2d)^2 + s^2}$$

$$d_{23}' = \sqrt{(2d)^2 + s^2}$$

$$d_{31}' = \sqrt{(2d)^2 + (2s)^2}$$

$$d_{32}' = \sqrt{(2d)^2 + s^2}$$

5. Two Circuit Flat



$$d_{12}' = \sqrt{(2d + 2s)^2 + s^2}$$

$$d_{13}' = \sqrt{(2d + 2s)^2 + (2s)^2}$$

$$d_{14}' = 2d + s$$

$$d_{15}' = \sqrt{(2d + s)^2 + (s)^2}$$

$$d_{16}' = \sqrt{(2d + s)^2 + (2s)^2}$$

$$d_{21}' = \sqrt{(2d + 2s)^2 + (s)^2}$$

$$d_{23'} = \sqrt{(2d + 2s)^2 + (s)^2}$$

$$d_{24'} = \sqrt{(2d + s)^2 + (s)^2}$$

$$d_{25'} = 2d + s$$

$$d_{26'} = (2d + s)^2 + (s)^2$$

$$d_{31'} = \sqrt{(2d + 2s)^2 + (s)^2}$$

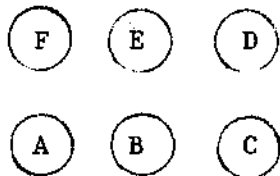
$$d_{32'} = \sqrt{(2d + 2s)^2 + s^2}$$

$$d_{34'} = \sqrt{(2d + s)^2 + s^2}$$

$$d_{35'} = \sqrt{(2d + s)^2 + s^2}$$

$$d_{36'} = 2d + s$$

6. Two Circuit Flat Reversed Phase



$$d_{12}' = \sqrt{(2d + 2S)^2 + S^2}$$

$$d_{13}' = \sqrt{(2d + 2S)^2 + (2S)^2}$$

$$d_{14}' = \sqrt{(2d + S)^2 + (2S)^2}$$

$$d_{15}' = \sqrt{(2d + S)^2 + S^2}$$

$$d_{16}' = 2d + S$$

$$d_{21}' = \sqrt{(2d + 2S)^2 + S^2}$$

$$d_{23}' = \sqrt{(2d + 2S)^2 + S^2}$$

$$d_{24}' = \sqrt{(2d + S)^2 + S^2}$$

$$d_{25}' = 2d + S$$

$$d_{26'} = \sqrt{(2d + s)^2 + s^2}$$

$$d_{31'} = \sqrt{(2d + 2s)^2 + s^2}$$

$$d_{32'} = \sqrt{(2d + 2s)^2 + s^2}$$

$$d_{34'} = 2d + s$$

$$d_{35'} = \sqrt{(2d + s)^2 + s^2}$$

$$d_{36'} = \sqrt{(2d + s)^2 + (2s)^2}$$

APPENDIX C

COMPUTER PROGRAM

In this appendix the complete computer program is listed. The main program appears first preceded a brief description of the input variables and their units.

The 12 subprograms follow the main program in alphabetical order. Each subprogram is preceded by a description of the output variable along with its units.

```

PROGRAM MAIN(INPUT,OUTPUT,TAPES=INPUT,TAPE6=OUTPUT)
THIS PROGRAM CALCULATES THE STEADY STATE AND TRANSIENT
TEMPERATURE DISTRIBUTION OF UNDERGROUND CABLES UNDER
FAULT CONDITIONS

THE FOLLOWING SYMBOLS ARE DEFINITIONS OF INPUT AND OUTPUT
VARIABLES ALONG WITH THEIR UNITS

C1,C2,C3,...,C10=CONSTANT COEFFICIENT.          DIMENSIONLESS
CPA=SPECIFIC HEAT OF AIR                        WATT-SEC/GM C
CPC=SPECIFIC HEAT OF CONDUCTOR.                WATT-SEC/GM C
CPE=SPECIFIC HEAT OF EARTH                      WATT-SEC/GM C
CPI=SPECIFIC HEAT OF INSIDE INSULATOR          WATT-SEC/GM C
CPO=SPECIFIC HEAT OF OUTSIDE INSULATOR         WATT-SEC/GM C
CPS=SPECIFIC HEAT OF SHIELD                    WATT-SEC/GM C
DIACH=DIA.OF CONDUCTOR WIPE                     CM
DIASW=DIA. OF SHIELD WIRES (IF ISHLD=2)        CM
FAULTI=FAULT CURRENT                            AMPS
FOC=FOURIER NUMBER OF CONDUCTOR                 DIMENSIONLESS
FOE=FOURIER NUMBER OF EARTH                     DIMENSIONLESS
FOI=FOURIER NUMBER OF INSIDE INSULATOR         DIMENSIONLESS
FOO=FOURIER NUMBER OF OUTSIDE INSULATOR        DIMENSIONLESS
FOS=FOURIER NUMBER OF SHIELD                   DIMENSIONLESS
HSC=HEAT SOURCE OF CONDUCTOR                   DIMENSIONLESS
HSI=HEAT SOURCE OF INSIDE INSULATOR           DIMENSIONLESS
HSS=HEAT SOURCE OF SHIELD                      DIMENSIONLESS
IARNGE=1,2,3,4,5,6,
(CABLE CONFIGURATION FOR CASE 1,2,3,4,5,6)    DIMENSIONLESS
ICBL=1 , COPPER CONDUCTOR
      =2 , ALUMINUM CONDUCTOR                  DIMENSIONLESS
ICNTRL=1 , STEADY STATE CALCULATIONS ONLY
      =2 , BOTH STEADY STATE AND TRANSIENT
      CALCULATIONS
ISHLD=1 , SOLID SHIELD
      =2 , SHIELD COMPOSED OF INDIVIDUAL
      WIRES
II=CURRENT OF CABLE                             AMPS
KA=THERMAL CONDUCTIVITY OF AIR                  WATT/CM C
KC=THERMAL CONDUCTIVITY OF CONDUCTOR           WATT/CM C
KE=THERMAL CONDUCTIVITY OF EARTH               WATT/CM C
KEQUV=EQUIVALENT THERMAL CONDUCTIVITY OF
SHIELD LAYER                                    WATT/CM C
KT=THERMAL CONDUCTIVITY OF INSIDE INSULATOR   "
KO=THERMAL CONDUCTIVITY OF OUTSIDE INSULATOR  "
KS=THERMAL CONDUCTIVITY OF SHIELD              "
LAY=LAY OF SHIELD WIRES                        CM
LOADF=LOAD FACTOR                              DIMENSIONLESS
NC=NO. OF WIRES IN CONDUCTOR                   DIMENSIONLESS
NSW=NO. OF WIRES IN SHIELD (IF ISHLD=2)       DIMENSIONLESS
OVLAP=OVERLAP OF SHIELD MATERIAL              CM
PAREA=PERCENT AREA OF TOTAL SURFACE OF
SHIELD WIRES IN CONTACT WITH JACKET
MATERIAL                                        DIMENSIONLESS
PF=POWER FACTOR OF INSULATOR                  DIMENSIONLESS
RC=OUTSIDE RADIUS OF CONDUCTOR                 CM
RE=RADIUS OF EARTH TO LOCATION WHERE T=TEF    CM
RI=OUTSIDE RADIUS OF INSIDE INSULATOR         CM
RO=OUTSIDE RADIUS OF OUTSIDE INSULATOR        CM
RS=OUTSIDE RADIUS OF SHIELD                   CM
RESA=ELECTRIC RESISTIVITY TO AIR AT 25C       OHM-CM
RESC=ELECTRIC RESISTIVITY OF CONDUCTOR 25C    OHM-CM
RESS=ELECTRIC RESISTIVITY OF SHIELD           OHM-CM
RHOA=DENSITY OF AIR                            GM/CC
RHOC=DENSITY OF CONDUCTOR                      GM/CC

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C      RHOE=DENSITY OF EARTH          GM/CC          MAIN
C      RHOI=DENSITY OF INSIDE INSULATOR GM/CC          MAIN
C      RHOO=DENSITY OF OUTSIDE INSULATOR GM/CC          MAIN
C      RHOS=DENSITY OF SHIELD          GM/CC          MAIN
C      SPCAP=SPECIFIC CAPACITANCE OF DIELECTRIC DIMENSIONLESS MAIN
C      S=SPACING BETWEEN C.L. OF CALRES C              MAIN
C      TC=TEMPERATURE DISTRIBUTION OF CONDUCTOR C              MAIN
C      TE=TEMPERATURE DISTRIBUTION OF EARTH C              MAIN
C      TEF=TEMPERATURE OF AMBIENT EARTH C              MAIN
C      TI=TEMPERATURE DISTRIBUTION OF INSIDE INSULATOR C              MAIN
C      TO=TEMPERATURE DISTRIBUTION OF OUTSIDE INSULATOR C              MAIN
C      TOFF=TIME CIRCUIT IS OPEN SEC          MAIN
C      TON=TIME CIRCUIT IS FAULTED SEC          MAIN
C      TS=TEMPERATURE DISTRIBUTION OF SHIELD C              MAIN
C      VOLT=LINE TO NEUTRAL VOLTAGE VOLT          MAIN
C
C      MAIN PROGRAM BEGINS HERE          MAIN
C
C      DIMENSION TE(50),TO(50),TS(50),TI(50),TC(50),A(125),
18      B(125),C(125),D(125),T(125),IAS(5),
19      THETAC(125),THETAI(125),THETAS(125),THEYAO(125),THETAE(125),
20      PEE(50),ROO(50),RSS(50),RII(50),RCC(50),X(47),Y(47)
21      REAL KC,KI,KS,KO,KE,II,IS,ISA,ISB,ISC,KA,KEQUV,LAY,IAS,IM,KEE,
22      LOADF,LOSSF
23      COMMON /CBLGEO/RC,PI,RS,RO,S,ISHLD,IARNGE,NC,DIACH,DIASH,NSW,
24      ICBL,DEPTH,PAREA,OVRLAP,LAY/
25      2ELECPRP/SPCAP,II,FAULTI,VOLT,PF
26      3,TON1,TON2,TON3,TOFF1,TOFF2/
27      1THRMPRP/KC,KI,KO,KS,KA,RHOC,RHOI,RHOS,RHOO,CPC,CPI,CPS,CPO/
28      3ERTHPRP/KE,GPE,RHOE,TEF,RE,TCND,TSHLD,X,Y/
29      44ITSOP/FOC,FOS,FOO,FOE,FOI,HSC,HSJ,HSS,HSO,HSE,THETAC,THETAI,
30      THETAS,THEYAO,THETAE,DRD,DRI,D2S,DRO,DRE,REE,ROO,RSS,RII,RCC
31      EXTERNAL RESCOND,RESSHLD,SKINEFF,DIELOS,DINF,YINT,FCN,ODX,D2DX2,
32      HTSRCE
33      NAMELIST /CBLGEO/RC,PI,RS,RO,S,ISHLD,IARNGE,NC,DIACH,DIASH,NSW,
34      ICBL,DEPTH,PAREA,OVRLAP,LAY,ICNRL/
35      1THRMPRP/KC,KI,KO,KS,KA,RHOC,RHOI,RHOS,RHOO,RHOA,
36      ZCPA,CPC,CPI,CPS,CPO/
37      2ELECPRP/SPCAP,II,VOLT,PF,LOADF,
38      1FAULTI,TON1,TON2,TON3,TOFF1,TOFF2/
39      3ERTHPRP/KE,GPE,RHOE,TEF
40      READ (5,CBLGEO)
41      WRITE (6,CBLGEO)
42      READ (5,THRMPRP)
43      WRITE (6,THRMPRP)
44      READ (5,ELECPRP)
45      WRITE (6,ELECPRP)
46      READ (5,ERTHPRP)
47      WRITE (6,ERTHPRP)
48      READ (5,13) (X(I),I=1,47)
49      READ (5,13) (Y(I),I=1,47)
C
C      IF (ICBL .EQ. 1) GO TO 60
50      RESC=2.985E-06
51      RHOC=(RHOC*NC*(DIACH/2.0)**2+RHOA*(RC**2-NC*(DIACH/2.0)**2)
52      1/RC**2
53      CPC=(RHOC*CPC*NC*(DIACH/2.0)**2+RHOA*CPA*(RC**2-NC*(
54      1DIACH/2.0)**2))/(RC**2*RHOC)
55      GO TO 61
60      RESC=1.758E-06
61      RHOC=(RHOS*NC*(DIACH/2.0)**2+RHOA*(RC**2-NC*(DIACH/2.0)**2)
62      1/RC**2

```



```

102 CONTINUE
IF (N .GT. 1) GO TO 16
IF (ABS(TCOND-TC(12)) .GE. 5.0) GO TO 14
IF (ABS(TSHLD-TS(12)) .GE. 5.0) GO TO 14
GO TO 16
14 TCOND=TC(12)
TSHLD=TS(12)
TOUT=TD(25)
GO TO 1099
16 WRITE(6,102) M
WRITE(6,103)
WRITE(6,104)
WRITE(6,105)
DO 101 J=1,25
I=26-J
101 WRITE(6,202) REE(I),TE(I),ROO(I),TO(I),RSS(I),TS(I),
TRII(I),TI(I),RCC(I),TC(I)
IF (ICNTRL .EQ. 1) GO TO 9999
IF (N .EQ. 1) GO TO 2000
C
C INPUT AND OUTPUT FORMAT
C
13 FORMAT (10F6.2/10F6.2/10F6.2/10F6.2/7F6.2)
204 FORMAT (8X,*C1 =*E16.5/8X,*C3 =*E16.5/8X,*C4 =*E16.5
1/8X,*C5 =*E16.5/8X,*C6 =*E16.5/8X,*C7 =*E16.5/8X
2,*C8 =*E16.5/8X,*C10 =*E16.5/)
C
C CALCULATE TRANSIENT TEMPERATURE DISTRIBUTION
C
1112 DTAU=0.04*TON
M=125
TP=0.0
IND=0
KE=KEE
DO 2 I=2,24
A(I)=((1.0/(2.0*(I-1)*DRC*DRC))-1.0/(DRC*DRC))*DTAU*KC/
1(RHOCC*CPC)
B(I)=((2.0/(DRC*DRC))+1(RHOCC*CPC)/(DTAU*KC))*DTAU*KC/(RHOCC*CPC)
2 C(I)=((-1.0/(2.0*(I-1)*DRC*DRC))-1.0/(DRC*DRC))*DTAU*KC/
1(RHOCC*CPC)
DO 3 I=26,48
A(I)=((1.0/(2.0*(I-1)*DRI*DRI))-1.0/(DRI*DRI))*DTAU*KI/
1(RHOI*CPI)
B(I)=((2.0/(DRI*DRI))+1(RHOI*CPI)/(DTAU*KI))*DTAU*KI/(RHOI*CPI)
3 C(I)=((-1.0/(2.0*(I-1)*DRI*DRI))-1.0/(DRI*DRI))*DTAU*KI/
1(RHOI*CPI)
DO 4 I=50,72
A(I)=((1.0/(2.0*(I-1)*DRS*DRS))-1.0/(DRS*DRS))*DTAU*KS/
1(RHOS*CPS)
B(I)=((2.0/(DRS*DRS))+1(RHOS*CPS)/(DTAU*KS))*DTAU*KS/(RHOS*CPS)
4 C(I)=((-1.0/(2.0*(I-1)*DRS*DRS))-1.0/(DRS*DRS))*DTAU*KS/
1(RHOS*CPS)
DO 5 I=74,96
A(I)=((1.0/(2.0*(I-1)*DRO*DRO))-1.0/(DRO*DRO))*DTAU*KO/
1(RHOO*CPO)
B(I)=((2.0/(DRO*DRO))+1(RHOO*CPO)/(DTAU*KO))*DTAU*KO/(RHOO*CPO)
5 C(I)=((-1.0/(2.0*(I-1)*DRO*DRO))-1.0/(DRO*DRO))*DTAU*KO/
1(RHOO*CPO)
DO 6 I=98,120
A(I)=((1.0/(2.0*(I-1)*DRE*DRE))-1.0/(DRE*DRE))*DTAU*KE/
1(RHOE*CPE)
B(I)=((2.0/(DRE*DRE))+1(RHOE*CPE)/(DTAU*KE))*DTAU*KE/(RHOE*CPE)
6 C(I)=((-1.0/(2.0*(I-1)*DRE*DRE))-1.0/(DRE*DRE))*DTAU*KE/
1(RHOE*CPE)

```

```

1011 D(I)=T(I)+HSC*KC*DTAU*TEF/(RC**2*RHOC*CPC)
D(25)=D(1)*T(25)+CC
DO 1012 I=26,44
1012 D(I)=I(I)+HSI*KI*DTAU*TEF/(RI**2*RHOI*CPI)
D(49)=DS*T(49)+CI
DO 1013 I=50,72
1013 D(I)=T(I)+HSS*KS*DTAU*TEF/(RS**2*RHOS*CPS)
D(73)=DS*T(73)+CS
DO 1014 I=74,96
1014 D(I)=I(I)
D(97)=DE*T(97)
DO 1015 I=98,120
1015 D(I)=T(I)
CALL TRIDAG (1,121,A,B,C,D,T)
T(1)=T(2)
C
IF (TP-TON) 1025,1026,1026
1026 TP=TON
IND=1
1026 TXX=T(12)
TXY=T(52)
1029 WRITE (6,1104) TP
WRITE (6,104)
WRITE (6,105)
DO 1040 J=1,25
I=26-J
1040 WRITE (6,202) PEE(I),T(I+96),ROO(I),T(I+72),RSS(I),
1T(I+48),RII(I),T(I+24),RCC(I),T(I)
IF (IND) 7,7,2000
2000 CONTINUE
C
C INPUT AND OUTPUT FORMAT
C
102 FORMAT (1H1,/60X,*CABLE*,3X,I2)
103 FORMAT (/15X,*STEADY STATE TEMPERATURE DISTRIBUTION (DEG. C)
1AS A FUNCTION OF RADIAL POSITION (CM) * )
104 FORMAT (/8X,*EAPTH*,14X,*JACKET*,14X,*SHIELD*
1,13X,*INSULATOR*,10X,*CONDUCTOR*/)
105 FORMAT (4X,*RADIUS*,4X,*TEMP*,5X,*RADIUS*,4X,*TEMP*,
15X,*RADIUS*,4X,*TEMP*,6X,*RADIUS*,4X,*TEMP*,6X,*RADIUS*,4X,
2*TEMP*/)
202 FORMAT(10F10.5)
1100 FORMAT (8X,*WRONG*)
1101 FORMAT (8X,*WRONG AGAIN*)
1104 FORMAT (/5X,***** LOCAL TEMPERATURE DEGREES CENTIGRADE
1TIME IS *.E9.3,* SEC *****/)
9999 STOP
END
SUBROUTINE CURSHLD(RCOND,RSHL,ISA,ISB,ISC,QSA,QSB,QSC)
C
C TO CALCULATE INDUCED CURRENT SHEATH IN AMPS
C
COMMON /CBLGEO/RG,RI,RS,RC,S,ISHLD,IARNGE,NG,DIACW,DIASW,NSW,
1ICBL,DEPTH,PAREA,OVRLAP,LAY/
2ELECPRP/SPCAP,II,FAULTI,VOLT,PF,
3TON1,TON2,TON3,TOFF1,TOFF2/
1THR4PRP/KC,KI,KO,KS,KA,RMCC,RHOI,RHOS,RHOC,CPC,CPI,CPS,CPO
REAL KC,KI,KS,KO,II,ISA,ISB,ISC,KA,LAY
PRSS=30480.D*RSHL
XM=0.05292*ALOG10(S/((RS+PI)/2.))
A=0.0153333
B=0.03699617
GO TO (333,334,335,336,337,338) IARNGE
333 ISA=(XM**2/(RRCSS**2+XM**2))**0.5*II

```



```

R14=LOSSF*(2.0*DEPTH+S)/KE EFFKE
R15=LOSSF*ALOG(SQRT((2.0*DEPTH+2.0*S)**2+S**2)/(1.4142*S))/KE EFFKE
R16=LOSSF*ALOG(SQRT((2.0*DEPTH+2.0*S)**2+(2.0*S)**2)/(2.236*S))/KE EFFKE
R21=R12 EFFKE
R23=R12 EFFKE
R24=R15 EFFKE
R25=R14 EFFKE
R26=R15 EFFKE
R31=R13 EFFKE
R32=R12 EFFKE
R34=R16 EFFKE
R35=R15 EFFKE
R36=R14 EFFKE
IF (M-2) 3651,3652,3653 EFFKE
3651 RCA=QSA*(RX1+RX2)+QSB*R12+QSC*R13+QSA*R14+QSB*R15+QSC*R16 EFFKE
GO TO 370 EFFKE
3652 RCA=QSA*R21+QSB*(RX1+RX2)+QSC*R23+QSA*R24+QSB*R25+QSC*R26 EFFKE
GO TO 370 EFFKE
3653 RCA=QSA*R31+QSB*R32+QSC*(RX1+RX2)+QSA*R34+QSB*R35+QSC*R36 EFFKE
GO TO 370 EFFKE
366 P12=LOSSF*ALOG(SQRT((2.0*DEPTH+2.0*S)**2+S**2)/S)/KE EFFKE
R13=LOSSF*ALOG(SQRT((2.0*DEPTH+2.0*S)**2+(2.0*S)**2)/(2.0*S))/KE EFFKE
R14=LOSSF*ALOG(SQRT((2.0*DEPTH+S)**2+(2.0*S)**2)/(2.236*S))/KE EFFKE
R15=LOSSF*ALOG(SQRT((2.0*DEPTH+S)**2+S**2)/(1.4142*S))/KE EFFKE
R16=LOSSF*(2.0*DEPTH+S)/KE EFFKE
P21=R12 EFFKE
P23=R12 EFFKE
P24=R15 EFFKE
P25=R16 EFFKE
P26=R15 EFFKE
P31=R13 EFFKE
P32=R23 EFFKE
P34=R16 EFFKE
P35=R15 EFFKE
P36=R14 EFFKE
IF (M-2) 3661,3662,3663 EFFKE
3661 RCA=QSA*(RX1+RX2)+QSB*R12+QSC*R13+QSA*R16+QSB*R15+QSC*R14 EFFKE
GO TO 370 EFFKE
3662 RCA=QSA*R21+QSB*(RX1+RX2)+QSC*R23+QSA*R26+QSB*R25+QSC*R24 EFFKE
GO TO 370 EFFKE
3663 RCA=QSA*R31+QSB*R32+QSC*(RX1+RX2)+QSA*R36+QSB*R35+QSC*R34 EFFKE
370 EFFKE=ALOG(DINFN/TWORO)/RCA EFFKE
WRITE (5,371) EFFKE EFFKE
371 FORMAT (8X,*EFFKE =*E16.7) EFFKE
RETURN EFFKE
END EFFKE
SUBROUTINE HTSORCE (IS,IM,TON,RCOND,PSHLD,SKEFF,DLOSS, HTSORCE
1HSC,HSI,HSS,FDC,FOI,FOS,FOO,FOE) HTSORCE
C TO CALCULATE HEAT SOURCE AND FOURIER NUMBER FOR CONDUCTOR, HTSORCE
C INSULATOR, AND SHIELD BOTH ARE DIMENSIONLESS HTSORCE
C HTSORCE
C DIMENSION X(47),Y(47) HTSORCE
COMMON /CBLGEO/RC,RI,RS,RO,S,ISHLD,IARNGE,NC,DIACW,DIASW,NSW, HTSORCE
1ICBL,DEPTH,PAREA,OVPLAP,LAY/ HTSORCE
ZELECRP/SPCAP,II,FAULTI,VOLY,PF, HTSORCE
3TON1,TON2,TON3,TOFF1,TOFF2/ HTSORCE
1THRMPR/KC,KI,KO,KS,KA,RHCC,RHOI,PHOS,RHOO,CPC,GPI,CPS,CPO/ HTSORCE
3ERTHPR/KE,CPE,RHOE,TEF,RE,TCOND,TSHLD,X,Y HTSORCE
PEAL IS,KC,KS,II,KI,KO,KE,IM,LAY,KA HTSORCE
IF (ISHLD.GT.1) GO TO 371 HTSORCE
370 HSS=IS**2*RSHLD*RS**2/(3.1416*(RS**2-RI**2)*KS*TEF) HTSORCE
GO TO 372 HTSORCE
371 HSS=IS**2*RSHLD*RS**2/(3.1416*(DIASW**2/4.)*NSW*KS*TEF) HTSORCE

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372 HSC=I4**2*RCND*PC**2*SKEFF/(3.1416*(DIAGW/2.))**2*NC*KC*TEF) HTSORCE
HSI=DLLOSS*RI**2/(3.1416*(RI**2-RC**2)*KI*TEF) HTSORCE
FOC=KC*TON/(RHOC*CPC*RC**2) HTSORCE
FOE=KE*TON/(RHOE*CPE*RE**2) HTSORCE
FOI=KI*TON/(PHOI*CPI*RI**2) HTSORCE
FOO=KO*TON/(RHOOC*PO*RO**2) HTSORCE
FOS=KS*TON/(RHOS*CPS*RS**2) HTSORCE
WRITE (6,373)HSC,HSS,HSI,FOC,FOS,FOI,FOO,FOE HTSORCE
373 FORMAT(8X,*HSC=*E18.7/8X,*HSS=*E18.7/8X,*HSI=*E18.7/ HTSORCE
24X,*FOC=*E18.7/8X,*FOS=*E18.7/8X,*FOI=*E18.7, HTSORCE
3/8X,*FOO=*E18.7/8X,*FOE=*E18.7) HTSORCE
RETURN HTSORCE
END HTSORCE
SUBROUTINE KEQUV (KS,KA,RI,RS,DIASW,NSW,PAREA,RHOS,RHOA,CPS,CPA) KEQUV
C TO CALCULATE EQUIVALENT THERMAL CONDUCTIVITY,DENSITY,SPECIFIC HEAT KEQUV
C AND AIR GAP WHEN SHIELD CONSISTS OF WIRES, KEQUV IN WATTS/CM C KEQUV
C CPA IN WATTS SEC/GM C, AND RHOS IN GM/CC KEQUV
C REAL KA,KS KEQUV
C PI=3.14159 KEQUV
C PHI=PI*PAREA KEQUV
C PSI=DIASW*PHI/(2.0*RI) KEQUV
C THETA=(2.0*PI-NSW*PSI)/NSW KEQUV
C KS=(NSW/(2.0*PI))*(PSI*KS+THETA*KA) KEQUV
C RHOS=(PHOS*(DIASW/2.0)**2*NSW+RHOA*(RS**2-RI**2)-(DIASW/2.0) KEQUV
C 1**2*NSW)/(RS**2-PI**2) KEQUV
C CPS=(DIASW/2.0)**2*NSW*PHOS*CPS+(((RS**2-RI**2)-(DIASW/2.0) KEQUV
C 1**2*NSW)*RHOA*CPA)/(RS**2-RI**2)*RHOS) KEQUV
C PHOS=RHOSS KEQUV
C WRITE (6,381) KS KEQUV
381 FORMAT (8X,*KEQUV=*E15.7) KEQUV
RETURN KEQUV
END KEQUV
FUNCTION RESCOND (TCOND,NC,DIAGW,ICBL) RESCOND
C TO CALCULATE D.C. ELECTRICAL RESISTANCE OF CONDUCTOR PER CM LENGTH RESCOND
C IN OHMS/CM AND TO ACCOUNT FOR VARIATION OF RESISTANCE WITH RESCOND
C CONDUCTOR TEMPERATURE, BOTH ALUMINUM AND COPPER RESCOND
C CONDUCTORS ARE CONSIDERED RESCOND
C IF (ICBL.EQ.1) GO TO 10 RESCOND
C RESC=2.885E-06 RESCOND
C GO TO 20 RESCOND
10 RESC=1.758E-06 RESCOND
20 RESC025=RESC/(NC*3.1416*(DIAGW/2.))**2) RESCOND
C IF (ICBL.GT.1) GO TO 311 RESCOND
C RESCOND=(234.+TCOND)*RESC025/259. RESCOND
C GO TO 312 RESCOND
311 RESCOND=(228.+TCOND)*RESC025/253. RESCOND
312 WRITE (6,310) RESCOND RESCOND
310 FORMAT (8X,*RESCOND=*E15.7) RESCOND
RETURN RESCOND
END RESCOND
FUNCTION RESSHLD (ISHLD,NSW,DIASW,TSHLD,RI,RS,CVRLAP,LAY) RESSHLD
C TO CALCULATE D.C. ELECTRICAL RESISTANCE OF SHIELD PER CM LENGTH RESSHLD
C IN OHMS/CM AND TO ACCOUNT FOR VARIATION OF RESISTANCE WITH RESSHLD
C SHIELD TEMPERATURE. ONLY COPPER SHIELDS ARE CONSIDERED. RESSHLD
C FACTOR OF 1.3 IS CORRUGATION CORRECTION FACTOR. RESSHLD
C REAL LAY RESSHLD
C RESS=1.758E-06 RESSHLD
C IF (ISHLD.GT.1) GO TO 321 RESSHLD

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