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SUBJECT: Forwards addl info re Thermo-Lag related ampacity derating calculations,as requested by NRC 950306 ltr.

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May 12, 1995 AEP:NRC:0692DF

Docket Nos.: 50-315
50-316

U. S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, D. C. 20555

Gentlemen:

Donald C. Cook Nuclear Plant Units 1 and 2
ADDITIONAL INFORMATION REGARDING THERMO-LAG
RELATED AMPACITY DERATING CALCULATIONS
TAC NOS. M85538 AND M85539

By your letter dated March 6, 1995, we were requested to submit representative ampacity derating calculations with respect to cables in raceways covered with Thermo-Lag used at Donald C. Cook Nuclear Plant. The calculations and methodologies, including mathematical models, are addressed in the attachments to this letter.

Attachment 1 provides an overall summary of our ampacity derating analyses. Attachment 2 contains the basis of our mathematical model. Attachment 3 contains cable tray allowable fill design criteria. Attachment 4 provides an in-depth discussion of the development of the mathematical model and analysis. Attachment 5 contains representative calculation results. Attachment 6 provides results from tests used to verify the accuracy of our computer model.

Sincerely,

E. E. Fitzpatrick

E. E. Fitzpatrick
Vice President

cad

Attachments

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ATTACHMENT 1 TO AEP:NRC:0692DF

SUMMARY OF AMPACITY DERATING ANALYSES

...9505190297

1.0 Background

In the early 1980's, compliance with 10CFR50 Appendix "R" was achieved for Cook Nuclear Plant (CNP) by enclosing certain raceways with Thermal Science Incorporated (TSI) Thermo-Lag 330-1 fire barriers. Enclosing the power cable raceways with the TSI material increases the thermal resistance to ambient thus restricting the quantity of heat released, resulting in reduced conductor allowable ampacity.

Although TSI material specifications addressed specific percent derating for the cables in tray and conduit wrapped with Thermo-Lag barriers, AEPSC took an aggressive approach to independently determine the reduced allowable ampacities and documented that the full load currents for power cables in the TSI wrapped raceways at CNP did not exceed allowable derated ampacities.

2.0 Theoretical analysis/ Mathematical model

The process included the development of a mathematical model based on the theoretical analysis and work done by Neher, McGrath, and Buller in their AIEE transactions papers 57-660 and 50-52 (attachment 2). This analysis is based on the phenomena of heat transfer with respect to energized cables and the effect on the ampacity.

The temperature rating of a cable is the maximum conductor temperature that will not cause excessive deterioration of the cable insulation over the expected life of the cable. This maximum temperature limits the amount of heat which may be generated by a conductor by resistive heating and therefore limits the amount of current the cable can carry.

Enclosing the conductor within layers of material (i.e.,insulation, raceway, or air space) increases the thermal resistance to the ambient heat sink and restricts the quantity of heat which may be transferred while still maintaining the maximum conductor temperature.

The objective then was to determine the allowable ampacity of cables in various raceway and fire protected raceway configurations based on the heat transfer through a thermal resistance while not exceeding the temperature rating of the cables under steady state conditions.

The phenomena of heat transfer with respect to energized cables and the effect on cable ampacity were examined. This included:

a) review of basic heat transfer mechanics,

b) evaluation of previous work done in the areas of cable ampacity and heat transfer,

c) analysis of the effects of conduction, convection and radiation with respect to CNP power cable installations, and

d) development of heat transfer theory for low fill cable trays.

Per our design criteria (see attachment 3), the power cables installed in cable trays are positioned in a single layer with a minimum space between cables of 1/3 the diameter of the larger adjacent cable. Furthermore, the sum of cable diameters can not exceed 75% of the tray width. The above criteria limits the number of power cables installed in a cable tray, thus limiting the total heat generated per foot and limiting the conductor derating.

3.0 Calculations

A computer program was developed according to the criteria outlined in the mathematical model. The program calculates the allowable ampacities for the power cables in the TSI wrapped raceways. Assuming a maximum allowable cable temperature of 90°C and an ambient temperature of 40°C, the maximum allowable heat generated(Q) was calculated for steady state conditions. The allowable ampacity (I) was then calculated using the known relationship between Q and I. The analysis and mathematical model are discussed in depth in attachment 4.

At CNP, the power cables in all TSI wrapped raceways were analyzed using this program and it was documented that the cable full load currents are within the calculated allowable ampacities. Representative calculation results showing the allowable ampacities for the cable tray and conduit raceway design are included in attachment 5.

4.0 Tests

Finally, a series of tests was conducted in 1983 at our Canton test lab to verify the accuracy of the computer model. These tests simulated exact raceway loading conditions at CNP and demonstrated that the conductor temperatures for the TSI enclosed cables are within the temperature rating of the conductors as predicted by the computer model. Refer to attachment 6 for the test report #CL-542 dated December 16, 1983. The highest conductor temperature recorded for the six tested configurations was 68.8°C. Cable trays and conduits were both included in this testing.

5.0 Conclusion

At CNP, the calculations for the cables enclosed with TSI Thermo-Lag 330-1 fire barriers demonstrated that:

a) the connected full load currents are well within calculated allowable ampacities,

b) the calculated heat generated per foot of raceway is well under the calculated allowable heat generation per foot of raceway, and

c) the raceway design criteria limits the total number of cables in a raceway such that the cable temperature ratings are not exceeded.

ATTACHMENT 2 TO AEP:NRC:0692DF

AIEE TRANSACTIONS PAPERS 57-660 & 50-52

[illegible]

The Calculation of the Temperature Rise and Load Capability of Cable Systems

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IN 1932 D. M. Simmons[1] published a series of articles entitled, "Calculation of the Electrical Problems of Underground Cables." Over the intervening 25 years this work has achieved the status of a handbook on the subject. During this period, however, there have been numerous developments in the cable art, and much theoretical and experimental work has been done with a view to obtaining more accurate methods of evaluating the parameters involved. The advent of the pipe-type cable system has emphasized the desirability of a more rational method of calculating the performance of cables in duct in order that a realistic comparison may be made between the two systems.

In this paper the authors have endeavored to extend the work of Simmons by presenting under one cover the basic principles involved, together with more recently developed procedures for handling such problems as the effect of the loading cycle and the temperature rise of cables in various types of duct structures. Included as well are expressions required in the evaluation of the basic parameters for certain specialized allied procedures. It is thought that a work of this type will be useful not only as a guide to engineers entering the field and as a reference to the more experienced, but particularly as a basis for setting up computation methods for the preparation of industry load capability and a-c/d-c ratio compilations.

The calculation of the temperature rise of cable systems under essentially steady-state conditions, which includes the effect of operation under a repetitive load cycle, as opposed to transient temperature rises due to the sudden application of large amounts of load, is a relatively simple procedure and involves only the application of the thermal equivalents of Ohm's and Kirchoff's Laws to a relatively simple thermal circuit. Because this circuit usually has a number of parallel paths with heat flows entering at several points, however, care must be exercised in the method used of expressing the heat flows and thermal resistances involved, and differing methods are used by various engineers. The method employed in this paper has been selected after careful consideration as being the most consistent and most readily handled over the full scope of the problem.

All losses will be developed on the basis of watts per conductor foot. The heat flows and temperature rises due to dielectric loss and to current-produced losses will be treated separately, and, in the latter case, all heat flows will be expressed in terms of the current produced loss originating in one foot of conductor by means of multiplying factors which take into account the added losses in the sheath and conduit.

In general, all thermal resistances will be developed on the basis of the per conductor heat flow through them. In the case of underground cable systems, it is convenient to utilize an effective thermal resistance for the earth portion of the thermal circuit which includes the effect of the loading cycle and the mutual heating effect of the other cable of the system. All cables in the system will be considered to carry the same load currents and to be operating under the same load cycle.

The system of nomenclature employed is in accordance with that adopted by the Insulated Conductor Committee as standard, and differs appreciably from that used in many of the references. This system represents an attempt to utilize in so far as possible the various symbols appearing in the American Standards Association Standards for Electrical Quantities, Mechanics, Heat and Thermo-Dynamics, and Hydraulics, when these symbols can be used without ambiguity. Certain symbols which have long been used by cable engineers have been retained, even though they are in direct conflict with the above-mentioned standards.

Nomenclature

(AF) = attainment factor, per unit (pu)
A_s = cross-section area of a shielding tape or skid wire, square inches
α = thermal diffusivity, square inches per hour
CI = conductor area, circular inches
d = distance, inches
d_{12} etc. = from center of cable no. 1 to center of cable no. 2 etc.
d_{12}' etc. = from center of cable no. 1 to image of cable no. 2 etc.
d_{1i} etc. = from center of cable no. 1 to a point of interference
d_{1i}' etc. = from image of cable no. 1 to a point of interference
D = diameter, inches
~~D_o = inside of annular conductor~~ — not hollow
D_c = outside of conductor
D_i = outside of insulation
D_s = outside of sheath
D_{sm} = mean diameter of sheath
D_j = outside of jacket
D_s' = effective (circumscribing circle) of several cables in contact
D_p = inside of duct wall, pipe or conduit
D_e = diameter at start of the earth portion of the thermal circuit
D_x = fictitious diameter at which the effect of loss factor commences
E = line to neutral voltage, kilovolts (kv)
ϵ = coefficient of surface emissivity
ϵ_r = specific inductive capacitance of insulation
f = frequency, cycles per second
F, F_{int} = products of ratios of distances
$F(x)$ = derived Bessel function of x (Table III and Fig. 1)
G = geometric factor
G_1 = applying to insulation resistance (Fig. 2 of reference 1)
G_2 = applying to dielectric loss (Fig. 2 of reference 1)
G_b = applying to a duct bank (Fig. 2)
I = conductor current, kiloamperes
k_s = skin effect correction factor for annular and segmental conductors
k_p = relative transverse conductivity factor for calculating conductor proximity effect
l = lay of a shielding tape or skid wire, inches
L = depth of reference cable below earth's surface, inches
L_b = depth to center of a duct bank (or backfill), inches
(lf) = load factor, per unit
(LF) = loss factor, per unit
n = number of conductors per cable
n' = number of conductors within a stated diameter
N = number of cables or cable groups in a system
P = perimeter of a duct bank or backfill, inches
$\cos\phi$ = power factor of the insulation
q_s = ratio of the sum of the losses in the conductors and sheaths to the losses in the conductors
q_c = ratio of the sum of the losses in the conductors, sheath and conduit to the losses in the conductors
R = electrical resistance, ohms
R_{dc} = d-c resistance of conductor
R_{ac} = total a-c resistance per conductor
R_s = d-c resistance of sheath or of the parallel paths in a shield-skid wire assembly
$\bar{R}$ = thermal resistance (per conductor losses) thermal ohm-feet
$\bar{R}_i$ = of insulation
$\bar{R}_j$ = of jacket
$\bar{R}_{sd}$ = between cable surface and surrounding enclosure

Paper 57-660, recommended by the AIEE Insulated Conductors Committee and approved by the AIEE Technical Operations Department for presentation at the AIEE Summer General Meeting, Montreal, Que., Canada, June 24–28, 1957. Manuscript submitted March 20, 1957; made available for printing April 18, 1957.

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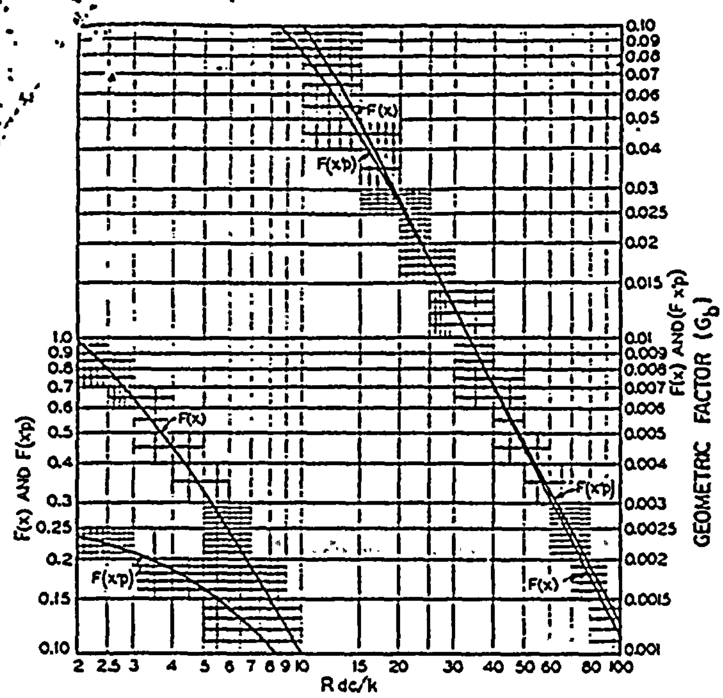
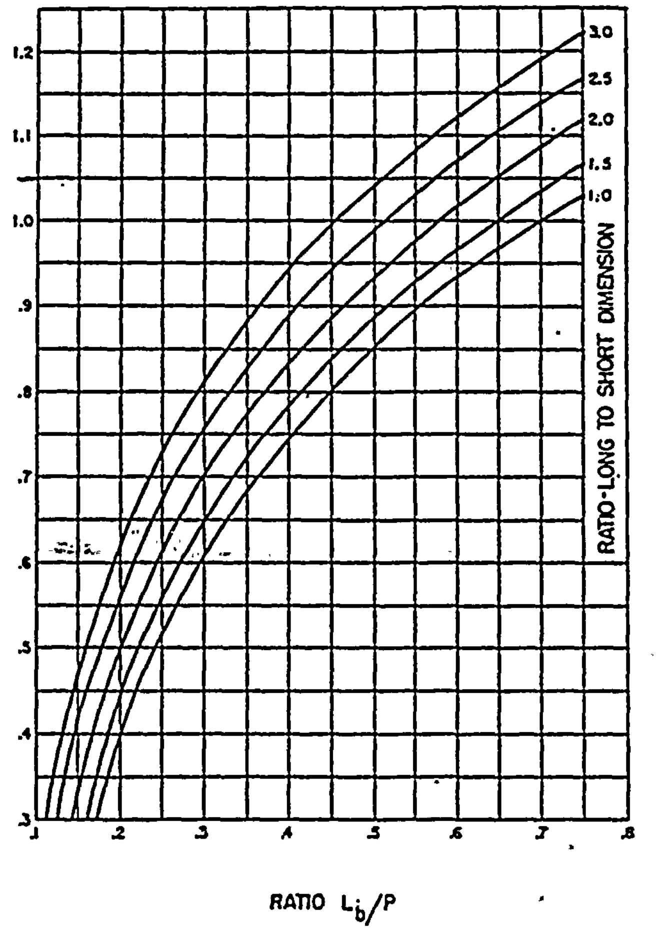


Fig. 1 (above). F(x) and F(x_p') as functions of R_{dc}/k

Fig. 2 (right). G_b for a duct bank



R_d = of duct wall or asphalt mastic covering
$\bar{R}_{sd}$ = total between sheath and diameter D_e including $\bar{R}_j$, $\bar{R}_{sd}$ and $\bar{R}_d$
$\bar{R}_e$ = between conduit and ambient
$\bar{R}_e'$ = effective between diameter D_e and ambient earth including the effects of loss factor and mutual heating by other cables
$\bar{R}_{ca}'$ = effective between conductor and ambient for conductor loss
R_{ct}' = effective transient thermal resistance of cable system
$\bar{R}_{da}'$ = effective between conductor and ambient for dielectric loss
$\bar{R}_{int}$ = of the interference effect
$\bar{R}_{ya}$ = between a steam pipe and ambient earth
ρ = electrical resistivity, circular mil ohms per foot
$\bar{\rho}$ = thermal resistivity, degrees centigrade centimeters per watt
s = distance in a 3-conductor cable between the effective current center of the conductor and the axis of the cable, inches
S = axial spacing between adjacent cables, inches
t, T = thickness (as indicated), inches
T = temperature, degrees centigrade
T_a = of ambient air or earth
T_c = of conductor
T_m = mean temperature of medium
ΔT = temperature rise, degrees centigrade
ΔT_c = of conductor due to current produced losses
ΔT_d = of conductor due to dielectric loss
ΔT_{int} = of a cable due to extraneous heat source
τ = inferred temperature of zero resistance, degrees centigrade (C) (used in correcting R_{dc} and R_t to temperatures other than 20 C)
V_w = wind velocity, miles per hour
W = losses developed in a cable, watts per conductor foot
W_c = portion developed in the conductor
W_s = portion developed in the sheath or shield
W_p = portion developed in the pipe or conduit
W_d = portion developed in the dielectric
X_m = mutual reactance, conductor to sheath or shield, microhms per foot
Y = the increment of a-c/d-c ratio, pu
Y_c = due to losses originating in the conductor, having components Y_{cs} due to skin effect and Y_{cp} due to proximity effect
Y_s = due to losses originating in the sheath or shield, having components Y_{sc} due to circulating current effect and Y_{se} due to eddy current effect
Y_p = due to losses originating in the pipe or conduit
Y_a = due to losses originating in the armor

General Considerations of the Thermal Circuit

The Calculation of Temperature Rise

The temperature rise of the conductor of a cable above ambient temperature may be considered as being composed of a temperature rise due to its own losses, which may be divided into a rise due to current produced (I^2R) losses (hereinafter referred to merely as losses) in the conductor, sheath and conduit ΔT_c and the rise produced by its dielectric loss ΔT_d. Thus

$$T_c - T_a = \Delta T_c + \Delta T_d \text{ degrees centigrade} \tag{1}$$

Each of these component temperature rises may be considered as the result of a rate of heat flow expressed in watts per foot through a thermal resistance expressed in thermal ohm feet (degrees centigrade feet per watt); in other words, the radial rise in degrees centigrade for a heat flow of one watt uniformly distributed over a conductor length of one foot.

Since the losses occur at several positions in the cable system, the heat flow in the thermal circuit will increase in steps. It is convenient to express all heat flows in terms of the loss per foot of conductor, and thus

$$\Delta T_c = W_c(\bar{R}_i + q_s\bar{R}_{sd} + q_e\bar{R}_e) \text{ degrees centigrade} \tag{2}$$

in which W_c represents the losses in one conductor and $\bar{R}_i$ is the thermal resistance of the insulation, q_s is the ratio of the sum of the losses in the conductors and sheath to the losses in the conductors, $\bar{R}_{sd}$ is the total thermal resistance between sheath and conduit, q_e is the ratio of the sum of the losses in conductors, sheath and conduit, to the conductor losses, and $\bar{R}_e$

is the 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). Hence, the losses in the cable will vary according to the corresponding daily loss cycle having a loss factor (LF). From an examination of a large number of load cycles and their corresponding load and loss factors, the following general relationship between load factor and loss factor has been found to exist.[2]

$$(LF) = 0.3\,(lf) + 0.7\,(lf)^2 \text{ per unit} \qquad (3)$$

In order to determine the maximum temperature rise attained by a buried cable system under a repeated daily load cycle, the losses and resultant heat flows are calculated on the basis of the maximum load (usually taken as the average current for that hour of the daily load cycle during which the average current is the highest, i.e. the daily maximum one-hour average load) on which the loss factor is based and the heat flow in the last part of the earth portion of the thermal circuit is reduced by the factor (LF). If this reduction is considered to start at a point in the earth corresponding to the diameter D_x,[3] equation 2 becomes

$$\Delta T_c = W_c[\bar{R}_i + q_s\bar{R}_{sd} + q_e(\bar{R}_{ex} + (LF)\bar{R}_{xa})] \text{ degrees centigrade} \qquad (4)$$

In effect this means that the temperature rise from conductor to D_x is made to depend on the heat loss corresponding to the maximum load whereas the temperature rise from diameter D_x to ambient is made to depend on the average loss over a 24-hour period. Studies indicate that the procedure of assuming a fictitious critical diameter D_x at which an abrupt change occurs in loss factor from 100% to actual will give results which very closely approximate those obtained by rigorous transient analysis. For cables or duct in air where the thermal storage capacity of the system is relatively small, the maximum temperature rise is based upon the heat flow corresponding to maximum load without reduction of any part of the thermal circuit.

When a number of cables are installed close together in the earth or in a duct bank, each cable will have a heating effect upon all of the others. In calculating the temperature rise of any one cable, it is convenient to handle the heating effects of the other cables of the system by suitably modifying the last term of equation 4. This is permissible since it is assumed that all the cables are carrying equal currents, and are operating on the same load cycle. Thus for an N-cable system

$$\Delta T_c = W_c(\bar{R}_i + q_s\bar{R}_{sd} + q_e[\bar{R}_{ex} + (LF)\times(\bar{R}_{xa}) + (N-1)\bar{R}_{pa}]) \qquad (5)$$

$$= W_c(\bar{R}_i + q_s\bar{R}_{sd} + q_e\bar{R}_e{}') \text{ degrees centigrade} \qquad (5A)$$

where the term in parentheses is indicated by the effective thermal resistance $\bar{R}_e{}'$.

The temperature rise due to dielectric loss is a relatively small part of the total temperature rise of cable systems operating at the lower voltages, but at higher voltages it constitutes an appreciable part and must be considered. Although the dielectric losses are distributed throughout the insulation, it may be shown that for single conductor cable and multiconductor shielded cable with round conductors the correct temperature rise is obtained by considering for transient and steady state that all of the dielectric loss W_d occurs at the middle of the thermal resistance between conductor and sheath or alternately for steady-state conditions alone that the temperature rise between conductor and sheath for a given loss in the dielectric is half as much as if that loss were in the conductor. In the case of multiconductor belted cables, however, the conductors are taken as the source of the dielectric loss.[1]

The resulting temperature rise due to dielectric loss ΔT_d may be expressed

$$\Delta T_d = W_d\bar{R}_{da}{}' \text{ degrees centigrade} \qquad (6)$$

in which the effective thermal resistance $\bar{R}_{da}{}'$ is based upon $\bar{R}_i$, $\bar{R}_{sd}$, and $\bar{R}_e{}'$ (at unity loss factor) according to the particular case. The temperature rise at points in the cable system other than at the conductor may be determined readily from the foregoing relationships.

The Calculation of Load Capability

In many cases the permissible maximum temperature of the conductor is fixed and the magnitude of the conductor current (load capability) required to produce this temperature is desired. Equation 5(A) may be written in the form

$$\Delta T_c = I^2 R_{dc}(1 + Y_c)\bar{R}_{ca}{}' \text{ degrees centigrade} \qquad (7)$$

in which the quantity $R_{dc}\,(1+Y_c)$ which will be evaluated later represents the effective electrical resistance of the conductor in microhms per foot and which when multiplied by I^2 (I in kiloamperes) will equal the loss W_c in watts per conductor foot actually generated in the conductor; and $\bar{R}_{ca}{}'$ is the effective thermal resistance of the thermal circuit.

$$\bar{R}_{ca}{}' = \bar{R}_i + q_s\bar{R}_{sd} + q_e\bar{R}_e{}' \text{ thermal ohm-feet} \qquad (8)$$

From equation 1 it follows that

$$I = \sqrt{\frac{T_c - (T_a + \Delta T_d)}{R_{dc}(1 + Y_c)\bar{R}_{ca}{}'}} \text{ kiloamperes} \qquad (9)$$

Table I. Electrical Resistivity of Various Materials

Material	Circular Mil Ohms per Foot at 20 C	τ, C
Copper (100% IACS*)	10.371	234.5
Aluminum (61% IACS)	17.002	228.1
Commercial Bronze (43.6% IACS) (90 Cu-10 Zn)	23.8	564
Brass (27.3% IACS) (70 Cu-30 Zn)	38.0	912
Lead (7.84% IACS)	132.3	236

* International Annealed Copper Standard.

Calculation of Losses and Associated Parameters

Calculation of D-C Resistances

The resistance of the conductor may be determined from the following expressions which include a lay factor of 2%; see Table I.

$$R_{dc} = \frac{1.02\rho_c}{CI} \text{ microhms per foot at 20 C} \qquad (10)$$

$$= \frac{12.9}{CI} \text{ for 100\% IACS copper conductor at 75 C} \qquad (10A)$$

$$= \frac{21.2}{CI} \text{ for 61\% IACS aluminum at 75 C} \qquad (10B)$$

where CI represents the conductor size in circular inches and where ρ_c represents the electrical resistivity in circular mil ohms per foot. To determine the value of resistance at temperature T multiply the resistance at 20 C by $(\tau+T)/(\tau+20)$ where τ is the inferred temperature of zero resistance.

The resistance of the sheath is given by the expressions

$$R_s = \frac{\rho_s}{4D_{sm}t} \text{ microhms per foot at 20 C} \qquad (11)$$

$$R_s = \frac{37.9}{D_{sm}t} \text{ for lead at 50 C} \qquad (11A)$$

$$= \frac{4.75}{D_{sm}t} \text{ for 61\% aluminum at 50 C} \qquad (11B)$$

where D_{sm} is the mean diameter of the sheath and t is its thickness, both in inches

$$D_{sm} = D_s - t \text{ inches} \qquad (12)$$

The resistance of intercalated shields or skid wires may be determined from the expression

$$R_s \text{ (per path)} = \frac{\pi\rho_s}{4A_s}\sqrt{1 + \left(\frac{\pi D_{sm}}{l}\right)^2} \text{ microhms per foot at 20 C} \qquad (13)$$

where A_s is the cross-section area of the

tape or skid wire and l is its lay. The over-all resistance of the shield and skid wire assembly, particularly for nonintercalated shields, should be determined by electrical measurement when possible.

Calculation of Losses

It is convenient to develop expressions for the losses in the conductor, sheath and pipe or conduit in terms of the components of the a-c/d-c ratio of the cable system which may be expressed as follows[4]

$$R_{ac}/R_{dc}=1+Y_c+Y_s+Y_p \quad (14)$$

The a-c/d-c ratio at conductor is $1+Y_c$

and at sheath or shield is $1+Y_c+Y_s$

and at pipe or conduit is $1+Y_c+Y_s+Y_p$

The corresponding losses physically generated in the conductor, sheath, and pipe are

$$W_c=I^2R_{dc}(1+Y_c) \text{ watts per conductor foot} \quad (15)$$

$$W_s=I^2R_{dc}Y_s \text{ watts per conductor foot} \quad (16)$$

$$W_p=I^2R_{dc}Y_p \text{ watts per conductor foot} \quad (17)$$

This permits a ready determination of the losses if the segregated a-c/d-c ratios are known, and conversely, the a-c/d-c ratio is readily obtained after the values of Y_c, Y_s and Y_p have been calculated.

It follows from the definitions of q_s and q_e that

$$q_s=\frac{W_c+W_s}{W_c}=1+\frac{Y_s}{1+Y_c} \quad (18)$$

$$q_e=\frac{W_c+W_s+W_p}{W_c}=1+\frac{Y_s+Y_p}{1+Y_c} \quad (19)$$

The factor Y_c is the sum of two components, Y_{cs} due to skin effect and Y_{cp} due proximity effect.

$$W_c=I^2R_{dc}(1+Y_{cs}+Y_{cp}) \text{ watts per conductor foot} \quad (20)$$

The skin effect may be determined from the skin effect function $F(x)$

$$Y_{cs}=F(x_s) \quad (21)$$

$$x_s=0.875\sqrt{\frac{fk_s}{R_{dc}}}=\frac{6.80}{\sqrt{R_{dc}/k_s}} \text{ at 60 cycles} \quad (22)$$

in which the factor k_s depends upon the conductor construction. For solid or conventional conductors appropriate values of k_s will be found in Table II. The function $F(x)$ may be obtained from Table III or from the curves of Fig. 1 in terms of the ratio R_{dc}/k at 60 cycles.

For annual conductors

$$k_s=\frac{D_c-D_o}{D_c+D_o}\left(\frac{D_c+2D_o}{D_c+D_o}\right)^2 \quad (23)$$

in which D_c and D_o represent the outer and inner diameters of the annular conductor. In comparison with the rigorous Bessel function solution for the skin effect in an isolated tubular conductor, it has been found that the 60-cycle skin effect of annular conductor when computed by equation 23 will not be in error by more than 0.01 in absolute magnitude for copper or aluminum IPCEA (Insulated Power Cable Engineers Association) filled

Table II. Recommended Values of k_s and k_p

Conductor Construction	Coating on Strands	Treatment	k_s	k_p
Concentric round	None	None	1.0	1.0
Concentric round	Tin or alloy	None	1.0	1.0
Concentric round	None	Yes	1.0	0.80
Compact round	None	Yes	1.0	0.6
Compact segmental	None	None	0.435	0.6
Compact segmental	Tin or alloy	None	0.5	0.7
Compact segmental	None	Yes	0.435	0.37
Compact sector	None	Yes	1.0	(see note)

Notes:

1. The term "treated" denotes a completed conductor which has been subjected to a drying and impregnating process similar to that employed on paper power cable.

2. Proximity effect on compact sector conductors may be taken as one-half of that for compact round having the same cross-sectional area and insulation thickness.

3. Proximity effect on annular conductors may be approximated by using the value for a concentric round conductor of the same cross-sectional area and spacing. The increased diameter of the annular type and the removal of metal from the center decreases the skin effect but, for a given axial spacing, tends to result in an increase in proximity.

4. The values listed above for compact segmental refer to four segment constructions. The "uncoated-treated" values may also be taken as applicable to four segment compact segmental with hollow core (approximately 0.75 inch clear). For "uncoated-treated" six segment hollow core compact segmental limited test data indicates k_s and k_p values of 0.39 and 0.33 respectively.

Table III. Skin Effect in % in Solid Round Conductor and in Conventional Round Concentric Strand Conductors

100 F(x), Skin Effect %

x	0	1	2	3	4	5	6	7	8	9
0.3	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
0.4	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03
0.5	0.03	0.04	0.04	0.04	0.05	0.05	0.05	0.06	0.06	0.06
0.6	0.07	0.07	0.08	0.08	0.09	0.10	0.10	0.11	0.11	0.12
0.7	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.19	0.20
0.8	0.21	0.22	0.24	0.25	0.26	0.28	0.29	0.30	0.31	0.33
0.9	0.34	0.36	0.38	0.39	0.41	0.43	0.45	0.47	0.48	0.50
1.0	0.52	0.54	0.56	0.58	0.61	0.63	0.65	0.68	0.70	0.73
1.1	0.76	0.79	0.81	0.84	0.87	0.90	0.94	0.97	1.00	1.03
1.2	1.07	1.11	1.14	1.18	1.22	1.26	1.30	1.34	1.38	1.42
1.3	1.47	1.52	1.56	1.61	1.66	1.71	1.76	1.81	1.86	1.92
1.4	1.97	2.02	2.08	2.14	2.20	2.26	2.32	2.39	2.45	2.52
1.5	2.58	2.65	2.72	2.79	2.86	2.93	3.01	3.08	3.16	3.24
1.6	3.32	3.40	3.49	3.57	3.66	3.75	3.83	3.92	4.02	4.11
1.7	4.21	4.30	4.40	4.50	4.60	4.70	4.81	4.91	5.02	5.13
1.8	5.24	5.35	5.47	5.58	5.70	5.82	5.94	6.06	6.19	6.31
1.9	6.44	6.57	6.70	6.83	6.97	7.11	7.24	7.38	7.53	7.67
2.0	7.82	7.96	8.11	8.26	8.42	8.57	8.73	8.89	9.05	9.21
2.1	9.38	9.54	9.71	9.88	10.05	10.22	10.40	10.58	10.76	10.94
2.2	11.13	11.31	11.50	11.69	11.88	12.07	12.27	12.47	12.67	12.87
2.3	13.07	13.27	13.48	13.68	13.90	14.11	14.33	14.54	14.76	14.98
2.4	15.21	15.43	15.66	15.89	16.12	16.35	16.58	16.82	17.16	17.30
2.5	17.54	17.78	18.03	18.27	18.52	18.78	19.03	19.28	19.54	19.80
2.6	20.06	20.32	20.58	20.85	21.12	21.38	21.65	21.93	22.20	22.48
2.7	22.75	23.03	23.31	23.60	23.88	24.17	24.45	24.74	25.03	25.33
2.8	25.62	25.92	26.21	26.51	26.81	27.11	27.42	27.72	28.03	28.34
2.9	28.65	28.96	29.27	29.58	29.90	30.21	30.53	30.85	31.17	31.49
3.0	31.81	32.13	32.45	32.78	33.11	33.44	33.77	34.10	34.43	34.77
3.1	35.10	35.44	35.78	36.11	36.45	36.79	37.13	37.47	37.82	38.16
3.2	38.50	38.85	39.20	39.55	39.89	40.24	40.59	40.94	41.29	41.65
3.3	42.00	42.35	42.71	43.06	43.42	43.78	44.14	44.49	44.85	45.21
3.4	45.57	45.93	46.29	46.66	47.02	47.38	47.74	48.11	48.47	48.84
3.5	49.20	49.57	49.94	50.30	50.67	51.04	51.40	51.77	52.14	52.51
3.6	52.88	53.25	53.62	53.99	54.36	54.73	55.10	55.48	55.85	56.22
3.7	56.59	56.96	57.33	57.71	58.08	58.45	58.82	59.20	59.57	59.94
3.8	60.31	60.69	61.06	61.44	61.81	62.18	62.56	62.93	63.30	63.68
3.9	64.05	64.42	64.80	65.17	65.55	65.92	66.29	66.67	67.04	67.41
4.0	67.79	68.16	68.53	68.91	69.28	69.65	70.03	70.40	70.77	71.14
4.1	71.52	71.89	72.26	72.63	73.00	73.38	73.75	74.12	74.49	74.86
4.2	75.23	75.60	75.97	76.34	76.71	77.08	77.45	77.82	78.19	78.56
4.3	78.93	79.30	79.67	80.04	80.41	80.78	81.14	81.51	81.88	82.25
4.4	82.61	82.98	83.35	83.61	84.08	84.45	84.81	85.18	85.55	85.91
4.5	86.28	86.64	87.01	87.37	87.73	88.10	88.46	88.82	89.19	89.55
4.6	89.91	90.28	90.64	91.00	91.37	91.73	92.09	92.45	92.81	93.17
4.7	93.53	93.89	94.25	94.61	94.97	95.33	95.69	96.05	96.41	96.77
4.8	97.13	97.49	97.85	98.21	98.57	98.92	99.28	99.64	100.00	100.35
4.9	100.71	101.07	101.42	101.78	102.14	102.49	102.85	103.21	103.56	103.92

Table IV. Mutual Reactance at 60 Cycles, Conductor to Sheath (or Shield)

$D_{sm}/2S$	--0	1	2	3	4	5	6	7	8	9
0.4	21.1	20.5	19.9	19 4	18.9	18.3	17.8	17.4	16.9	16.4
0.3	27.7	26.9	26.2	25.5	24.8	24.1	23.5	22.9	22.2	21.6
0.2	37.0	35.9	34.8	33.8	32.8	31.9	31.0	30.1	29.3	28.4
0.1	52.9	50.7	48.7	46.9	45.2	43.6	42.1	40.7	39.4	38.2

core conductors up through 5.0 *CI* and for hollow core concentrically stranded copper or aluminum oil-filled cable conductors up through 4.0 *CI*.

For values of x_p below 3.5, a range which appear to cover most cases of practical interest at power frequencies, the conductor proximity effect for cables in equilateral triangular formation in the same or in separate ducts may be calculated from the following equation based on an approximate expression given by Arnold[6] (equation 7) for a system of three homogeneous, straight, parallel, solid conductors of circular cross section arranged in equilateral formation and carrying balanced 3-phase current remote from all other conductors or conducting material. The empirical transverse conductance factor k_p is introduced to make the expression applicable to stranded conductors. Experimental results suggest the values of k_p shown in Table II.

$$Y_{cp}=F(x_p)\left(\frac{D_c}{S}\right)^2\times\left[\frac{1.18}{F(x_p)+0.27}+0.312\left(\frac{D_c}{S}\right)^2\right] \quad (24)$$

$$x_p=\frac{6.80}{\sqrt{R_{dc}/k_p}} \text{ at 60 cycles} \quad (25)$$

When the second term in the brackets is small with respect to the first term as it usually is, equation 24 may be written

$$Y_{cp}=4F(x_p)\left[\frac{0.295(D_c/S)^2}{F(x_p)+0.27}\right]=4\left(\frac{D_c}{S}\right)^2F(x_p') \quad (24A)$$

where the function $F(x_p')$ is shown in Fig. 1.

The average proximity effect for conductors in cradle configuration in the same duct or in separate ducts in a formation approximating a regular polygon may also be estimated from equation 24 and 24(A). In such cases, S should be taken as the axial spacing between adjacent conductors.

The factor Y_s is the sum of two factors, Y_{sc} due to circulating current effect and Y_{se} due to eddy current effects.

$$W_s=I^2R_{dc}(Y_{sc}+Y_{se}) \text{ watts per conductor foot} \quad (26)$$

Because of the large sheath losses which result from short-circuited sheath operation with appreciable separation between metallic sheathed single conductor cables, this mode of operation is usually restricted to triplex cable or three single-conductor cables contained in the same duct. The circulating current effect in three metallic sheathed single-conductor cables arranged in equilateral configuration is given by

$$Y_{sc}=\frac{R_s/R_{dc}}{1+(R_s/X_m)^2} \quad (27)$$

When $(R_s/X_m)^2$ is large with respect to unity as usually is the case of shielded nonleaded cables, equation 27 reduces to

$$Y_{sc}=\frac{X_m}{R_sR_{dc}} \text{ approximately} \quad (27A)$$

$$X_m=0.882f\log 2S/D_{sm} \text{ microhms per foot} \quad (28)$$

$$=52.9\log 2S/D_{sm} \text{ microhms per foot at 60 cycles} \quad (28A)$$

where S is the axial spacing of adjacent cables. For a cradled configuration X_m may be approximated from

$$X_m=52.9\log\frac{2.52S}{D_{sm}}\sqrt{1-\left(\frac{S}{D_p-S}\right)^2} \text{ microhms per foot at 60 cycles} \quad (29)$$

$$=52.9\log 2.3\, S/D_{sm} \text{ approximately} \quad (29A)$$

Table IV provides a convenient means for determining X_m for cables in equilateral configuration.

The eddy-current effect for single-conductor cables in equilateral configuration with open-circuited sheaths is

$$Y_{se}=\frac{3R_s/R_{dc}}{\left(\frac{5.2R_s}{f}\right)^2+\frac{1}{5}\left(\frac{2S}{D_{sm}}\right)^2}\times\left(\frac{D_{sm}}{2S}\right)^2\left[1+\frac{5}{12}\left(\frac{D_{sm}}{2S}\right)^2\right] \quad (30)$$

when $(5.2\, R_s/f)^2$ is large in respect to 1/5 $(2\,S/D_{sm})$ as in the case of lead sheaths.

$$Y_{se}=\frac{396}{R_sR_{dc}}\left(\frac{D_{sm}}{2S}\right)^2\left[1+\frac{5}{12}\left(\frac{D_{sm}}{2S}\right)^2\right] \text{ approximately at 60 cycles} \quad (30A)$$

When the sheaths are short-circuited, the sheath eddy loss will be reduced and may be approximated by multiplying equations 30 or 30(A) by the ratio

$R_s^2/(R_s^2+X_m^2)$

In computing average eddy current for cradled configuration, S should be taken equal to the axial spacing and not to the geometric-mean spacing. Equations 30 and 30(A) may be used to compute the eddy-current effect for single-conductor cables installed in separate ducts. Strictly speaking, these equations apply only to three cables in equilateral configuration but can be used to estimate losses in large cable groups when latter are so oriented as to approximate a regular polygon.

The eddy-current effect for a 3-conductor cable is given by Arnold.[6]

$$Y_{se}=\frac{3R_s}{R_{dc}}\left[\frac{(2s/D_{sm})^2}{\left(\frac{5.2R_s}{f}\right)^2+1}+\frac{(2s/D_{sm})^4}{4\left(\frac{5.2R_s}{f}\right)^2+1}+\frac{(2s/D_{sm})^6}{16\left(\frac{5.2R_s}{f}\right)^2+1}\cdots\right] \quad (31)$$

When $(5.2R_s/f)^2$ is large with respect to unity,

$$Y_{se}=\frac{396}{R_sR_{dc}}\left(\frac{2s}{D_{sm}}\right)^2 \text{ approximately at 60 cycles} \quad (31A)$$

$$s=1.155T+0.60\times\text{the } V \text{ gauge depth for compact sectors}$$

$$=1.155T+0.58\,D_c \text{ for round conductors} \quad (32)$$

and T is the insulation thickness, including thickness of shielding tapes, if any. While equation 31(A) will suffice for lead sheath cables, equation 31 should be used for aluminum sheaths.

On 3-conductor shielded paper lead cable it is customary to employ a 3- or 5-mil copper tape or bronze tape intercalated with a paper tape for shielding and binder purposes. The lineal d-c resistance of a copper tape 5 mils by 0.75 inch is about 2,200 microhms per foot of tape at 20 C. The d-c resistance per foot of cable will be equal to the lineal resistance of the tape multiplied by the lay correction factor as given by the expression under the square-root sign in equation 13. In practice the lay correction factor may vary from 4 to 12 or more resulting in shielding and binder assembly resist-

Table V. Specific Inductive Capacitance of Insulations

Material	ϵ_r	
Polyethylene	2.3	
Paper insulation (solid type)	3.7	(IPCEA value)
Paper insulation (other types)	3.3–4.2	
Rubber and rubber-like compounds	5	(IPCEA value)
Varnished cambric	5	(IPCEA value)

ances of approximately 10,000 or more microhms per foot of cable. Even on the assumption that the assembly resistance is halved because of contact with adjacent conductors and the lead sheath computations made using equations 27 and 30 show that the resulting circulating and eddy current losses are a fraction of 1% on sizes of practical interest. For this reason it is customary to assume that the losses in the shielding and binder tapes of 3-conductor shielded paper lead cable are negligible. In cases of nonleaded rubber power cables where lapped metallic tapes are frequently employed, tube effects may be present and may materially lower the resistance of the shielding assembly and hence increase the losses to a point where they are of practical significance.

An exact determination of the pipe loss effect Y_p in the case of single-conductor cables installed in nonmagnetic conduit or pipe is a rather involved procedure as indicated in reference 7. Equation 31 may be used to obtain a rough estimate of Y_p for cables in cradled formation on the bottom of a nonmagnetic pipe, however by taking the average of the results obtained for wide triangular spacing with $s=(D_p-D_s)/2$ and for close triangle spacing at the center of the pipe with $s=0.578D_s$. The mean diameter of the pipe and its resistance per foot should be substituted for D_{sm} and R_s respectively.

For magnetic pipes or conduit the following empirical relationships[8] may be employed

$$Y_p=\frac{1.54s-0.115D_p}{R_{dc}} \text{ (3-conductor cable)} \quad (33)$$

$$Y_p=\frac{0.89S-0.115D_p}{R_{dc}} \text{(single-conductor, close triangular)} \quad (34)$$

$$Y_p=\frac{0.34S+0.175D_p}{R_{dc}} \text{(single-conductor, cradled)} \quad (35)$$

These expressions apply to steel pipe[8] and should be multiplied by 0.8 for iron conduit.[9]

The expressions given for Y_c and Y_s above should be multiplied by 1.7 to find the corresponding in-pipe effects for magnetic pipe or conduit for both triangular and cradled configurations.

Calculation of Dielectric Loss

The dielectric loss W_d for 3-conductor shielded and single-conductor cable is given by the expression

$$W_d=\frac{0.00276E^2\epsilon_r\cos\phi}{\log[(2T+D_c)/D_c]} \text{ watts per conductor foot at 60 cycles} \quad (36)$$

and for 3-conductor belted cable by[1]

$$W_d=\frac{0.019E^2\epsilon_r\cos\phi}{G_1} \text{ watts per conductor foot at 60 cycles} \quad (37)$$

where E is the phase to neutral voltage in kilovolts, ϵ_r is the specific inductive capacitance of the insulation (Table V) T is its thickness and $\cos\phi$ is its power factor. The geometric factor G_1 may be found from Fig. 2 of reference 1.

For compact sector conductors the dielectric loss may be taken equal to that for a concentric round conductor having the same cross-sectional area and insulation thickness.

Calculation of Thermal Resistance

Thermal Resistance of the Insulation

For a single conductor cable,

$$\bar{R}_i=0.012\bar{\rho}_i\log D_i/D_c \quad \text{thermal ohm-feet} \quad (38)$$

where $\bar{\rho}_i$ is the thermal resistivity of the insulation (Table VI) and D_i is its diameter. In multiconductor cables there is a multipath heat flow between the conductor and sheath. The following expression[1] represents an equivalent value which, when multiplied by the heat flow from one conductor, will produce the actual temperature elevation of the conductor above the sheath.

$$\bar{R}_i=0.00522\bar{\rho}_iG_1 \quad \text{thermal ohm-feet} \quad (39)$$

Values of the geometric factor G_1 for 3-conductor belted and shielded cables are given in Fig. 2 and Table VIII respectively of reference 1. On large size sector conductors with relatively thin insulation walls (i.e. ratios of insulation thickness to conductor diameter of the order of 0.2 or less); values of G_1 for 3-conductor shielded cable as determined by back calculation, on the basis of an assumed insulation resistivity, from laboratory heat-run temperature-rise data, have not always confirmed theoretical values, and, in some cases, have yielded G_1 values which approach those for a nonshielded, nonbelted construction.

Table VI. Thermal Resistivity of Various Materials

Material	$\bar{\rho}$, C Cm/Watt
Paper insulation (solid type)	700 (IPCEA value)
Varnished cambric	600 (IPCEA value)
Paper insulation (other types)	600–550
Rubber and rubber-like	500 (IPCEA value)
Jute and textile protective covering	600
Fiber duct	480
Polyethylene	450
Transite duct	200
Somastic	100
Concrete	85

Thermal Resistance of Jackets, Duct Walls, and Somastic Coatings

The equivalent thermal resistance of relatively thin cylindrical sections such as jackets and fiber duct walls may be determined from the expression

$$\bar{R}=0.0104\bar{\rho}n'\left(\frac{t}{D-t}\right) \quad \text{thermal ohm-feet} \quad (40)$$

with appropriate subscripts applied to $\bar{R}$, $\bar{\rho}$, and D in which D represents the outside diameter of the section and t its thickness. n' is the number of conductors contained with the section contributing to the heat flow through it.

Thermal Resistance between Cable Surface and Surrounding Pipe, Conduit, or Duct Wall

Theoretical expressions for the thermal resistance between a cable surface and a surrounding enclosure are given in reference 10. As indicated in Appendix I, these have been simplified to the general form

$$\bar{R}_{sd}=\frac{n'A}{1+(B+CT_m)D_s'} \quad \text{thermal ohm-feet} \quad (41)$$

in which A, B, and C are constants, D_s' represents the equivalent diameter of the cable or group of cables and n' the number of conductors contained within D_s'. T_m is the mean temperature of the intervening medium. The constants A, B, and C

Table VII. Constants for Use in Equations 41 and 41(A)

Condition	A	B	C	A'	B'
In metallic conduit	17	3.6	0.029	3.2	0.19
In fiber duct in air	17	2.1	0.016	5.6	0.33
In fiber duct in concrete	17	2.3	0.024	4.6	0.27
In transite duct in air	17	3.0	0.014	4.4	0.26
In transite duct in concrete	17	2.9	0.029	3.7	0.22
Gas-filled pipe cable at 200 psi	3.1	1.16	0.0053	2.1	0.69
Oil-filled pipe cable	0.84	0	0.0035	2.1	2.45

D_s' = 1.00 × diameter of cable for one cable
1.65 × diameter of cable for two cables
2.15 × diameter of cable for three cables
2.50 × diameter of cable for four cables

given in Table VII have been determined from the experimental data given in references 10 and 11.

If representative values of $T_m = 60$ C are assumed, equation 41 reduces to

$$\bar{R}_{sd} = \frac{n'A'}{D_s' + B'} \text{ thermal ohm-feet} \qquad (41A)$$

It should be noted that in the case of ducts, $\bar{R}_{sd}$ is calculated to the inside of the duct wall and the thermal resistance of the duct wall should be added to obtain $\bar{R}_{sa}$.

Thermal Resistance from Cables, Conduits, or Ducts Suspended in Air

The thermal resistance $\bar{R}_e$ between cables, conduits, or ducts suspended in still air may be determined from the following expression which is developed in Appendix I.

$$\bar{R}_e = \frac{15.6n'}{D_s'[(\Delta T/D_s')^{1/4} + 1.6\epsilon(1 + 0.0167T_m)]} \text{ thermal ohm-feet} \qquad (42)$$

In this equation ΔT represents the difference between the cable surface temperature T_s and ambient air temperature T_a in degrees centigrade, T_m the average of these temperatures and ϵ the coefficient of emissivity of the cable surface. Assuming representative values of $T_s = 60$ and $T_a = 30$ C, and a range in D_s' of from 2 to 10 inches, equation 42 may be simplified to

$$\bar{R}_e = \frac{9.5n'}{1 + 1.7D_s'(\epsilon + 0.41)} \text{ thermal ohm-feet} \qquad (42A)$$

The value of ϵ may be taken as equal to 0.95 for pipes, conduits or ducts, and painted or braided surfaces, and from 0.2 to 0.5 for lead and aluminum sheaths, depending upon whether the surface is bright or corroded. It is interesting to note that equation 42(A) checks the IPCEA method of determining R_e very closely with $\epsilon = 0.41$ for diameters up to 3.5 inches. In the IPCEA method $\bar{R}_e = 0.00411\ n'B/D_s'$ where $B = 650 + 314\ D_s'$ for

$D_s' = 0 - 1.75$ inches and $B = 1{,}200$ for larger values of D_s'

Effective Thermal Resistance Between Cables, Ducts, or Pipes, and Ambient Earth (CONCRETE)

As previously indicated, an effective thermal resistance $\bar{R}_e'$ may be employed to represent the earth portion of the thermal circuit in the case of buried cable systems. This effective thermal resistance includes the effect of loss factor and, in the case of a multicable installation, also the mutual heating effects of the other cables of the system. In the case of cables in a concrete duct bank, it is desirable to further recognize a difference between the thermal resistivity of the concrete $\bar{\rho}_c$ and the thermal resistivity of the surrounding earth $\bar{\rho}_e$.

The thermal resistance between any point in the earth surrounding a buried cable and ambient earth is given by the expression[12]

$$\bar{R}_{pa} = 0.012\bar{\rho}_e \log d'/d \quad \text{thermal ohm-feet} \qquad (43)$$

in which $\bar{\rho}_e$ is the thermal resistivity of the earth, d' is the distance from the image of the cable to the point P, and d is the distance from the cable center to P. From this equation and the principles discussed in references 3, 12, and 13, the following expressions may be developed, applicable to directly buried cables and to pipe-type cables.

$$\bar{R}_e' = 0.012\bar{\rho}_e n' \times \left[\log\frac{D_x}{D_e} + (LF)\log\left[\left(\frac{4L}{D_x}\right)F\right]\right] \text{ thermal ohm-feet} \qquad (44)$$

in which D_e is the diameter at which the earth portion of the thermal circuit commences and n' is the number of conductors contained within D_e. The fictitious diameter D_x at which the effect of loss factor commences is a function of the diffusivity of the medium α and the length of the loss cycle.[3]

$$D_x = 1.02\sqrt{\alpha(\text{length of cycle in hours})} \text{ inches} \qquad (45)$$

The empirical development of this equation is discussed in Appendix III. For a daily loss cycle and a representative value of $\alpha = 2.75$ square inches per hour for earth, D_x is equal to 8.3 inches. It should be noted that the value of D_x obtained from equation 45 is applicable for pipe diameters exceeding D_x, in which case the first term of equation 44 is negative.

The factor F accounts for the mutual heating effect of the other cables of the cable system, and consists of the product of the ratios of the distance from the reference cable to the image of each of the other cables to the distance to that cable. Thus,

$$F = \left(\frac{d_{12}'}{d_{12}}\right)\left(\frac{d_{13}'}{d_{13}}\right)\ldots\left(\frac{d_{1N}'}{d_{1N}}\right)(N-1 \text{ terms}) \qquad (46)$$

It will be noted that the value of F will vary depending upon which cable is selected as the reference, and the maximum conductor temperature will occur in the cable for which $4LF/D_x$ is a maximum. N refers to the number of cables or pipes, and F is equal to unity when $N = 1$.

When the cable system is contained within a concrete envelope such as a duct bank, the effect of the differing thermal resistivity of the concrete envelope is conveniently handled by first assuming that the thermal resistivity of the medium is that of concrete $\bar{\rho}_c$ throughout and then correcting that portion lying beyond the concrete envelope to the thermal resistivity of the earth $\bar{\rho}_e$. Thus

$$\bar{R}_e' = 0.012\bar{\rho}_c n' \times \left[\log\frac{D_x}{D_e} + (LF)\log\left[\left(\frac{4L}{D_x}\right)F\right]\right] + 0.012(\bar{\rho}_e - \bar{\rho}_c)n'N(LF)G_b \text{ thermal ohm-feet} \qquad (44A)$$

TOTAL

The geometric factor G_b, as developed in Appendix II is a function of the depth to the center of the concrete enclosure L_b and its perimeter P, and may be found conveniently from Fig. 2 in terms of the ratio L_b/P and the ratio of the longest to short dimension of the enclosure.

For buried cable systems T_a should be taken as the ambient temperature at the depth of the hottest cable. As indicated in reference 12, the expressions used throughout this paper for the thermal resistance and temperature rise of buried cable systems are based on the hypothesis suggested by Kennelly applied in accordance with the principle of superposition. According to this hypothesis, the isothermal-heat flow field and temperature rise at any point in the soil surrounding a buried cable can be represented by the steady-state solution for the heat flow between two parallel cylinders (constituting a heat source and sink) located in a vertical plane in an infinite medium of uniform temperature and thermal resistivity with an axial separation between cylinders of twice the actual depth of burial and with source and sink respectively generating and absorbing heat at identical rates, thereby resulting in the temperature of the horizontal midplane between cylinders (i.e., corresponding to the surface of the earth) remaining, by symmetry, undisturbed.

The principle of superposition, as applied to the case at hand, can be stated in thermal terms as follows: If the thermal network has more than one source of temperature rise, the heat that flows at any point, or the temperature drop between any two points, is the sum of the heat flows and temperature drops at these points which would exist if each source of temperature rise were considered separately. In the case at hand, the sources of heat flow and temperature rise to be superimposed are, namely, the heat

from the cable, the outward flow of heat from the core of the earth, and the inward heat flow solar radiation, and, when present, the heat flow from interfering sources. By employing as the ambient temperature in the calculations the temperature at the depth of burial of the hottest cable, the combined heat flow from earth core and solar radiation sources is superimposed upon that produced at the surface of the hottest cable by the heat flow from that cable and interfering sources which are calculated separately with all other heat flows absent. The combined heat flow from earth core and solar sources results in an earth temperature which decreases with depth in summer; increases with depth in winter; remains about constant at any given depth on the average over a year; approximates constancy at all depths at midseason, and in turn results in flow of heat from cable sources to earth's surface, directly to surface in midseason and winter and indirectly to surface in summer.

Factors which tend to invalidate the combined Kennelly-superposition principle method are departure of the temperature of the surface of earth from a true isothermal (as evidenced by melting of snow in winter directly over a buried steam main) and nonuniformity of thermal resistivity (due to such phenomena as radial and vertical migration of moisture). The extent to which the Kennelly-superposition principle method is invalidated, however, is not of practical importance provided that an over-all or effective thermal resistivity is employed in the Kennelly equation.

Special Conditions

Although the majority of cable temperature calculations may be made by the foregoing procedure, conditions frequently arise which require somewhat specialized treatment. Some of these are covered herein.

Emergency Ratings

Under emergency conditions it is frequently necessary to exceed the stated normal temperature limit of the conductor T_c and to set an emergency temperature limit T_c'. If the duration of the emergency is long enough for steady-state conditions to obtain, then the emergency rating I' may be found by equation 9 substituting T_c' for T_c and correcting R_{dc} or the increased conductor temperature.

If the duration of the emergency is less than that required for steady-state conditions to obtain, the emergency rating of the line may be determined from

$$I' = \sqrt{\frac{T_c' - I^2 R_{dc}(1+Y_c)(\bar{R}_{ca}' - \bar{R}_{ct}') - (T_a + \Delta T_d)}{R_{dc}'(1+Y_c)\bar{R}_{ct}'}} \text{ kiloamperes} \quad (47)$$

in which $\bar{R}_{ct}'$ is the effective transient thermal resistance of the cable system for the stated period of time. Procedures for calculating $\bar{R}_{ct}'$ for times up to several hours are given in reference 14, and for longer times in references 15-17.

The Effect of Extraneous Heat Sources

In the case of multicable installations the assumption has been made that all cables are of the same size and are similarly loaded. When this is not the case the temperature rise or load capability of one particular equal cable group may be determined by treating the heating effect of other cable groups separately, introducing an interference temperature rise ΔT_{int} in equations 1 and 9. Thus

$$T_c - T_a = \Delta T_c + \Delta T_d + \Delta T_{int} \text{ degrees centigrade} \quad (1A)$$

$$I = \sqrt{\frac{T_c - (T_a + \Delta T_d + \Delta T_{int})}{R_{dc}(1+Y_c)\bar{R}_{ca}'}} \text{ kiloamperes} \quad (9A)$$

in which ΔT_{int} represents the sum of a number of interference effects, for each of which

$$\Delta T_{int} = [W_c q_s (LF) + W_d]\bar{R}_{int} \text{ degrees centigrade} \quad (48)$$

$$\bar{R}_{int} = 0.012\bar{\rho}_e n' \log F_{int} \text{ thermal ohm-feet} \quad (49)$$

$$F_{int} = \frac{(d_{1t}')(d_{2t}')(d_{3t}')\ldots d_{Nt}'}{(d_{1t})(d_{2t})(d_{3t})\ldots d_{Nt}} \; (N \text{ terms}) \quad (50)$$

where the parameters apply to each system which may be considered as a unit. For cables in duct

$$\bar{R}_{int} = 0.012 n' [\bar{\rho}_e \log F_{int} + N(\bar{\rho}_c - \bar{\rho}_e)G_b] \text{ thermal ohm-feet} \quad (49A)$$

Because of the mutual heating between cable groups, the temperature rise of the interfering groups should be rechecked. If all the cable groups are to be given mutually compatible ratings, it is necessary to evaluate W_c for each group by successive approximations, or by setting up a system of simultaneous equations, substituting for W_c its value by equation 15 and solving for I.

In case ΔT_{int} or a component of it is produced by an adjacent steam main, the temperature of the steam T_v rather than the heat flow from it is usually given. Thus

$$\Delta T_{int} = \left[\frac{T_v - T_a}{\bar{R}_{va}}\right]\bar{R}_{int} \text{ degrees centigrade} \quad (51)$$

where $\bar{R}_{va}$ is the thermal resistance between the steam pipe and ambient earth.

Aerial Cables

In the case of aerial cables it may be desirable to consider both the effects of solar radiation which increases the temperature rise and the effect of the wind which decreases it.[24] Under maximum sunlight conditions, a lead-sheathed cable will absorb about 4.3 watts per foot per inch of profile[25] which must be returned to the atmosphere through the thermal resistance $\bar{R}_e/n'$. This effect is conveniently treated as an interference temperature rise according to the relationship

$$\Delta T_{int} = 4.3 D_s' \bar{R}_e / n' \text{ degrees centigrade} \quad (47A)$$

For black surfaces this value should be increased about 75%.

As indicated in Appendix II, the following expression for $\bar{R}_e$ may be used where V_w is the velocity of the wind in miles per hour

$$\bar{R}_e = \frac{3.5n'}{D_s'(\sqrt{V_w/D_s'} + 0.62_e)} \text{ thermal ohm-feet} \quad (42B)$$

Use of Low-Resistivity Backfill

In cases where the thermal resistivity of the earth is excessively high, the value of $\bar{R}_e'$ may be reduced by backfilling the trench with soil or sand having a lower value of thermal resistivity. Equation 44(A) may be used for this case if $\bar{\rho}_f$, the thermal resistivity of the backfill is substituted for $\bar{\rho}_c$, and G_b applies to the zone having the backfill in place of the zone occupied by the concrete.

Single-Conductor Cables in Duct with Solidly Bonded Sheaths

The relatively large and unequal sheath losses in the three phases which may result from this type of operation may be determined from Table VI of reference 1. It will be noted that

$$Y_{sc1} = \left(\frac{R_s}{R_{dc}}\right)\left(\frac{I_{s1}^2}{I^2}\right); \quad Y_{sc2} = \left(\frac{R_s}{R_{dc}}\right)\left(\frac{I_{s2}^2}{I^2}\right);$$

$$Y_{sc3} = \left(\frac{R_s}{R_{dc}}\right)\left(\frac{I_{s3}^2}{I^2}\right) \quad (52)$$

where expressions for I_{s1}^2/I^2 etc., appear in the table. The resulting unequal values of Y_c in the three phases will yield unequal values of q_s, and equation 5 becomes for phase no. 1, the instance given as equation 5(A) on the following page.

$$\Delta T_{ct} = W_c[\bar{R}_i + q_{s1}\{\bar{R}_{sc} + \bar{R}_{cs} + (LF)\bar{R}_{sp}\} + Nq_{sa}(LF)\bar{R}_{pa}] \quad \text{thermal ohm-feet} \qquad (5A)$$

where q_{sa} is the average of q_{s1}, q_{s2}, and q_{s3}.

Armored Cables

In multiconductor armored cables a loss occurs in the armor which may be considered as an alternate to the conduit or pipe loss. If the armor is nonmagnetic, the component of armor loss Y_a to be used instead of Y_p in equations 14 and 19 may be calculated by the equations for sheath loss substituting the resistance and mean diameter of the armor for those of the sheath. In calculating the armor resistance, account should be taken of the spiralling effect for which equation 13 suitably modified may be used. If the armor is magnetic, one would expect an increase in the factors Y_c and Y_s in equation 14 since this occurs in the case of magnetic conduit. Unfortunately, no simple procedure is available for calculating these effects. A rough estimate of the inductive effects may be made by using the procedure given above for magnetic conduit.

A simple method of approximating the losses in single conductor cables with steel-wire armor at spacings ordinarily employed in submarine installations is to assume that the combined sheath and armor current is equal to the conductor current.[1] The effective a-c resistance of the armor may be taken as 30 to 60% greater than its d-c resistance corrected for lay as indicated above. If more accurate calculations are desired references 19 and 20 will be found useful.

Effect of Forced Cooling

The temperature rise of cables in pipes or tunnels may be reduced by forcing air axially along the system. Similarly, in the case of oil-filled pipe cable, oil may be circulated through the pipe. Under these conditions, the temperature rise is not uniform along the cable and increases in the direction of flow of the cooling medium. The solution of this problem is discussed in reference 21.

Table VIII. Constants for Use in Equation 53

Condition	a	b	c	Average ΔT
Cable in metallic conduit	0.07	0.121	0.0017	20
Cable in fiber duct in air	0.07	0.036	0.0009	20
Cable in fiber duct in concrete	0.07	0.043	0.0014	20
Cable in transite duct in air	0.07	0.086	0.0008	20
Cable in transite duct in concrete	0.07	0.079	0.0016	20
Gas-filled pipe-type cable at 200 psi	0.07	0.121	0.0017	10

Appendix I

Development of Equations 41, 42, and Table VII

Theoretical and semiempirical expressions for the thermal resistance between cables and an enclosing pipe or duct wall are given in reference 10. Further data on the thermal resistance between cables and fiber and transite ducts are given in reference 11. For purposes of cable rating, it is desirable to develop standardized expressions for these thermal resistances based upon all of the data available and including the effect of the temperature of the intervening medium.

The theoretical expression for the case where the intervening medium is air or gas as presented in reference 10 may be generalized in the following form:

$$\bar{R}_{sd} = \frac{n'}{D_s'\left[a\left(\frac{\Delta T P^2}{D_s'}\right)^{1/4} + b + cT_m\right]} \qquad (53)$$

where

$\bar{R}_{sd}$ = the effective thermal resistance between cable and enclosure in thermal ohm-feet

D_s' = the cable diameter or equivalent diameter of three cables in inches

ΔT = the temperature differential in degrees centigrade

P = the pressure in atmospheres

T_m = mean temperature of the medium in degrees centigrade

n' = number of conductors involved

The constants a, b, and c in this equation have been established empirically as follows: Considering $b+cT_m$ as a constant for the moment, the analysis given in reference 10 results in a value of $a=0.07$. With a thus established, the data given in reference 10 for cable in pipe, and in reference 11 for cable in fiber and transite ducts were analyzed in similar manner to give the values of b and c which are shown in Table VIII.

In order to avoid a reiterative calculation procedure, it is desirable to assume a value for ΔT since its actual value will depend upon $\bar{R}_{sd}$ and the heat flow. Fortunately, as ΔT occurs to the 1/4 power in equation 53, the use of an average value as indicated in Table VIII will not introduce a serious error.

By further restricting the range of D_s' to 1–4 inches for cable in duct or conduit and to 3–5 inches for pipe-type cables, equation 53 is reduced to equation 41.

$$\bar{R}_{sd} = \frac{n'A}{1+(B+CT_m)D_s'} \quad \text{thermal ohm-feet} \qquad (41)$$

in which the values of the constants A, B, and C appear in Table VII.

In the case of oil-filled pipe cable, the analysis given in reference 10 gives the following expression

$$\bar{R}_{sd} = \frac{n'}{0.60+0.025(D_s'^3 T_m^3 \Delta T)^{1/4}} \quad \text{thermal ohm-feet} \qquad (54)$$

Assuming an average value of $\Delta T=7$ C and a range of 150–350 for $D_s'T_m$, equation 54 reduces to equation 41 with the values of A, B, and C given in Table VII.

In the case of cables or pipes suspended in still air, the heat loss by radiation may be determined by the Stefan-Bolzmann formula

$$n'W\text{(radiation)} = 0.139D_s'\epsilon[(T_s+273)^4-(T_a+273)^4]10^{-8} \quad \text{watts per foot} \qquad (55)$$

where ϵ is the coefficient of emissivity of the cable or pipe surface. Over the limited temperature range in which we are interested, equation 55 may be simplified to[13]

$$n'W\text{(radiation)} = 0.102D_s'\Delta T\epsilon \times (1+0.0167T_m) \quad \text{watts per foot} \qquad (55A)$$

Over the same temperature range the heat loss by convection from horizontal cables or pipes is given with sufficient accuracy by the expression

$$n'W\text{(convection)} = 0.064\,D_s'\Delta T(\Delta T/D_s')^{1/4} \quad \text{watts per foot} \qquad (56)$$

in which the numerical constant 0.064 has been selected for the best fit with the carefully determined test results reported by Heilman[22] on 1.3, 3.5 and 10.8-inch diameter black pipes ($\epsilon=0.95$). Incidentally, this value also represents the best fit with the test data on 1.9–4.5 inch diameter black pipes reported by Rosch.[23] For vertical cables or pipes the value of this numerical constant may be increased by 22%.[22]

Combining equations 55(A) and 56 we obtain the relationship

$$\bar{R}_s = \frac{\Delta T}{n'W\text{(total)}} = \frac{15.6n'}{D_s'[(\Delta T/D_s')^{1/4}+1.6\epsilon(1+0.0167T_m)]} \quad \text{thermal ohm-feet} \qquad (42)$$

If the cable is subjected to wind having a velocity of V_w miles per hour, the following expression derived from the work of Schurig and Frick[24] should be substituted for the convection component.

$$n'W\text{(convection)} = 0.286D_s'\Delta T\sqrt{V_w/D_s'} \quad \text{watts per foot} \qquad (56A)$$

Combining equations 55(A) and 56(A) with $T_m=45$ C

$$\bar{R}_s = \frac{\Delta T}{n'W\text{(total)}} = \frac{3.5n'}{D_s'(\sqrt{V_w/D_s'}+0.62\epsilon)} \quad \text{thermal ohm-feet} \qquad (42B)$$

Appendix II

Determination of the Geometric Factor G_b for Duct Bank

Considering the surface of the duct bank to act as an isothermal circle of radius r_b, the thermal resistance between the duct bank and the earth's surface will be a logarithmic function of r_b and L_b the distance of the center of the bank below the surface. Using the long form of the Kennelly Formula[13] we may define the geometric factor G_b as

$$G_b = \log \frac{L_b + \sqrt{L_b^2 - r_b^2}}{r_b}$$

$$= \log\left[L_b/r_b + \sqrt{(L_b/r_b)^2 - 1}\right] \quad (57)$$

In order to evaluate r_b in terms of the dimensions of a rectangular duct bank, let the smaller dimension of the bank be x and the larger dimension by y. The radius of a circle inscribed within the duct bank touching the sides is

$$r_1 = x/2 \quad (58)$$

and the radius of a larger circle embracing the four corners is

$$r_2 = \frac{\sqrt{x^2+y^2}}{2} \quad (59)$$

Let us assume that the circle of radius r_b lies between these circles and the magnitude of r_b is such that it divides the thermal resistance between r_1 and r_2 in direct relation to the portions of the heat field between r_1 and r_2 occupied and unoccupied by the duct bank. Thus

$$\log \frac{r_b}{r_1} = \frac{xy - \pi r_1^2}{\pi(r_2^2 - r_1^2)}\left(\log \frac{r_2}{r_1}\right) \quad \text{or}$$

$$\log \frac{r_2}{r_b} = \frac{\pi r_2^2 - xy}{\pi(r_2^2 - r_1^2)}\left(\log \frac{r_2}{r_1}\right)$$

from which

$$\log\ r_b = \frac{1}{2}\,\frac{x}{y}\left(\frac{4}{\pi} - \frac{x}{y}\right) \log\left(1 + \frac{y^2}{x^2}\right) + \log \frac{x}{2} \quad (60)$$

It is desirable to derive r_b in terms of the perimeter P of the duct bank. Thus

$$P = 2(x+y) = 4\frac{x}{2}(1 + y/x)$$

and therefore

$$\log \frac{x}{2} = \log \frac{P}{4(1+y/x)} \quad (61)$$

The curves of Fig. 2 have been developed from equations 57, 60, and 61 for several values of the ratio y/x. It should be noted in passing that the value of $r_b = 0.112P$ used in reference 13 applies to a y/x ratio of about 2/1 only.

Appendix III

Empirical Evaluation of D_x

In order to evaluate the effect of a cyclic load upon the maximum temperature rise of a cable system simply, it is customary to assume that the heat flow in the final portion of the thermal circuit is reduced by a factor equal to the loss factor of the cyclic load. The point at which this reduction commences may be conveniently expressed in terms of a fictitious diameter D_x. Thus

$$\bar{R}_{ca}' = \bar{R}_{cx} + (LF)\bar{R}_{xa} \text{ thermal ohm-feet} \quad (62)$$

For greater accuracy, it is desirable to establish the value of D_x empirically rather than to assume that D_x is equal to the diameter D_e at which the earth portion of the thermal circuit commences.

Equation 62 may be written in the form

$$\bar{R}_{ca}' = \bar{R}_{ce} + \bar{R}_{ex} + (LF)(\bar{R}_{ea} - \bar{R}_{ex}) \text{ thermal ohm-feet} \quad (62A)$$

In terms of the attainment factor (AF), one may write

$$\bar{R}_{ca}' = (AF)\bar{R}_{ca} = (AF)(\bar{R}_{ce} + \bar{R}_{ea}) \text{ thermal ohm-feet} \quad (63)$$

Equating equations 62(A) and 63 obtains the relationship

$$\bar{R}_{ex} = (1-x)\bar{R}_{ea} - x\bar{R}_{ce} \text{ thermal ohm-feet} \quad (64)$$

where

$$x = \frac{1-(AF)}{1-(LF)} \quad (65)$$

Since

$$\bar{R}_{ex} = 0.012 n'\rho \log D_x/D_e \text{ thermal ohm-feet} \quad (66)$$

$$\log D_x/D_e = \frac{83}{n'\rho}[(1-x)\bar{R}_{ea} - x\bar{R}_{ce}] \quad (67)$$

The first paper of reference 3 presents the results of a study in which a number of typical daily loss cycles and also sinusoidal loss cycles of the same loss factor were applied to a number of typical buried cable systems. The results indicated that in all cases the sinusoidal loss cycle of the same loss factor adequately expressed the maximum temperature rise which was obtained with any of the actual loss cycles considered.

An analysis by equations 65 and 67 of the calculated values of attainment factors for sinusoidal loss cycles given in Table II and the corresponding cable system parameters given in Table I of the first paper of reference 3 yields a most probable value of $D_x = 8.3$ inches. As indicated in the third paper of reference 3, however, theoretically D_x should vary as the square root of the product of the diffusivity and the time length of the loading cycle. Hence as the diffusivity was taken as 2.75 square inches per hour in the above,

$$D_x = 1.02 \times \sqrt{\alpha_e \times \text{length of cycle in hours}} \text{ inches} \quad (45)$$

Table IX. Comparison of Values of % (AF) for Sinusoidal Loss Cycles at 30% Loss Factor

System	Description, Inches	% (AF) Neher	Shanklin	Wiseman
I	4.5 pipe	63/63	61/62	63/65
II	6.6 pipe	56/56	60/57	53/60
III	8.6 pipe	56/56	59/58	54/63
IV	10.6 pipe	58/58	61/59	55/53
V	0.5 cable		80/80	
VI	1.5 cable	77/76	77/76	77/77
VII	1.9 cable	71/71		
VIII	2.0 cable		63/62	
IX	2.0 cable		75/74	
X	3.4 cable		77/78	
Xa*	3.4 cable	83/80	83/81	
XI	3.7 cable	76/74	74/73	
XII	4.2 cable	70/66	70/67	
XIII	4.5 cable	69/64	65/64	61/63

* Diffusivity = 4.7 square inches per hour.

Table IX presents a comparison of the values of per cent attainment factor for sinusoidal loss cycles at 30% loss factor as calculated by equations 45, 66, 62(A), and 63 and as they appear in Table II of the first paper of reference 3.

Appendix IV. Calculations for Representative Cable Systems

15-Kv 350-MCM—3-Conductor Shielded Compact Sector Paper and Lead Cable Suspended in Air

$D_c = 0.616$ (equivalent round); V = gauge depth = 0.539 inch

$D_s = 2.129$; $T = 0.175$ inch; $t = 0.120$ inch

$$T_c = 81\text{ C};\ R_{dc} = \frac{12.9}{0.350}\left(\frac{234.5+81}{234.5+75}\right)$$

$= 37.6$ microhms per foot (Eq. 10A)

$D_{sm} = 2.129 - 0.120 = 2.009$ inches (Eq. 12)

$$R_s = \frac{37.9}{2.009(0.120)} = 157 \text{ microhms}$$

per foot at 50 C (Eq. 11A)

$k_s = 1.0$; $k_p = 0.6$ (equivalent round) (Table II)

$R_{dc}/k_s = 37.6$; $Y_{cs} = 0.008$ (Eq. 21 and Fig. 1)

$S = 0.616 + 2(0.175 + 0.008) = 0.982$ inches

$R_{dc}/k_p = 62.6$; $F(x_p') = 0.003$ (Fig. 1)

$$Y_{cp} = \frac{1}{2}\left[4\left(\frac{0.616}{0.982}\right)^2\right]0.003 = 0.002$$

(Eq. 24A, and note to Table II)

$1 + Y_c = 1 + 0.008 + 0.002 = 1.010$

$s = 1.155(0.175 + 0.008) + 0.60(0.539)$
$= 0.534$ inch (Eq. 32)

$$Y_s = Y_{ss} = \frac{396}{157(37.6)}\left\{\frac{2(0.534)}{2.009}\right\}^2 = 0.019$$

(Eq. 31A)

$R_{ac}/R_{dc} = 1.010 + 0.019 = 1.029$ (Eq. 14)

$$q_s = q_e = 1 + \frac{0.019}{1.010} = 1.019 \quad \text{(Eqs. 18–19)}$$

$\epsilon_r = 3.7$ (Table V); $E = 15/\sqrt{3} = 8.7$; $\cos\phi = 0.022$

$$W_d = \frac{0.00276\,(8.7)^2[3.7(0.022)]}{\log \dfrac{2(0.175)+0.681}{0.681}}$$

$= 0.094$ watt per conductor foot (Eq. 36 and text)

(Note: In computing dielectric loss on

sector conductors, the equivalent diameter of the conductor is taken equal to that of a concentric round conductor, i.e., 0.681 inch for 350 MCM.)

$\beta_t = 700$ (Table VI); $G_1 = 0.45$
(Table VIII of reference 1)

$\bar{R}_t = 0.00522\{700(0.45)\} = 1.64$
thermal ohm-feet (Eq. 39)

$n' = 3$; $\epsilon = 0.41$ (assumed)

$$\bar{R}_e = \frac{9.5(3)}{1+1.7[2.129(0.41+0.41)]}$$
$= 7.18$ thermal ohm-feet (Eq. 42A)

$\bar{R}_{ca} = 1.64 + 1.019(7.18) = 8.96$
thermal ohm-feet (Eq. 8)

$\Delta T_d = 0.094(0.82+7.18) = 0.75$ C (Eq. 6)

$T_a = 40$ C (assumed)

$$I = \sqrt{\frac{81-(40+0.8)}{37.6[1.010(8.96)]}}$$
$= 0.344$ kiloampere (Eq. 9)

If the cable is outdoors in sunlight and subjected to an 0.84 mile per hour wind

$$\bar{R}_e = \frac{3.5(3)}{2.129[\sqrt{0.84/2.129}+0.62(0.41)]}$$
$= 5.59$ thermal ohm-feet (Eq. 42B)

$\bar{R}_{ca}' = 1.64 + 1.019(5.59) = 7.34$
thermal ohm-feet (Eq. 8)

$$\Delta T_{int} = (4.3)(2.129)\left(\frac{5.59}{3}\right) = 17.1 \text{ C}$$
(Eq. 47A)

$T_a = 30$ C (assumed)

$$I = \sqrt{\frac{81-(30+0.6+17.1)}{(37.6)(1.010)(7.34)}}$$
$= 0.346$ kiloampere (Eq. 9)

In this particular case the net effect of solar radiation and an 0.84 mile per hour wind is to effectively raise the ambient temperature by 10 degrees, which is a rough estimating value commonly used. It should be noted, however, that this will not always be true, and the procedure outlined above is preferable.

69-Kv 1,500-MCM—Single-Conductor Oil-Filled Cable in Duct

Two identical cable circuits will be considered in a 2 by 3 fiber and concrete duct structure having the dimensions shown in Fig. 3.

$D_c = 0.600$; $D_c = 1.543$; $D_i = 2.113$;
$T = 0.235$; $D_s = 2.373$; $t = 0.130$ inches

$$T_c = 75 \text{ C}; \quad R_{dc} = \frac{12.9}{1.50} = 8.60$$
microhms per foot (Eq. 10A)

$D_{sm} = 2.373 - 0.130 = 2.243$ inches (Eq. 12)

$$R_s = \frac{37.9}{(2.243)(0.130)} = 130 \text{ microhms}$$
per foot at 50 C (Eq. 11A)

$$k_s = \frac{1.543-0.600}{1.543+0.600}\left(\frac{1.543+1.200}{1.543+0.600}\right)^2$$
$= 0.72$; $k_p = 0.8$ (Eq. 23 and Table II)

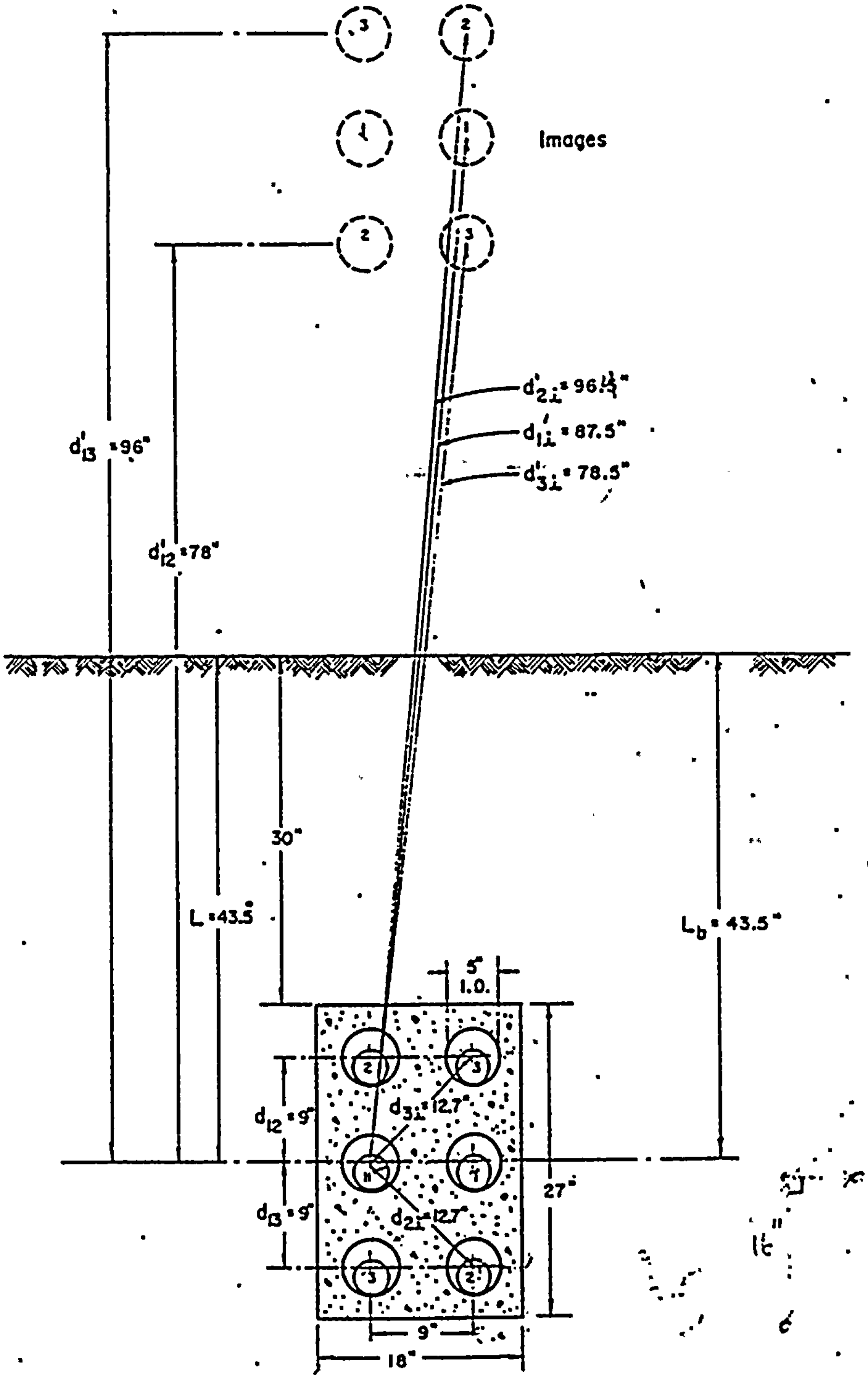


Fig. 3. Assumed duct bank configuration for typical calculations on 69-kv 1,500-MCM oil-filled cable (Appendix IV)

$Y_c = Y_{cs} + Y_{cp}$

$R_{dc}/k_s = 11.9$; $Y_{cs} = 0.075$
(Eq. 21 and Fig. 1)

$S = 9.0$ (Fig. 3); $R_{dc}/k_p = 10.75$;
$F(x_p') = 0.075$ (Fig. 1)

$$Y_{cp} = 4\left(\frac{1.412}{9.0}\right)^2 0.075 = 0.007 \quad \text{(Eq. 24A)}$$

$1 + Y_c = 1 + 0.075 + 0.007 = 1.082$

Assuming the sheaths to be open-circuited, $Y_{se} = 0$

$$Y_s = Y_{se} = \frac{396}{130(8.60)}\left(\frac{2.243}{2(9.0)}\right)^2 \times$$

$$\left[1+\frac{5}{12}\left(\frac{2.243}{2(9.0)}\right)^2\right] = 0.006 \quad \text{(Eq. 30A)}$$

$R_{ac}/R_{dc} = 1.082 + 0.006 = 1.088$ (Eq. 14)

$$q_s = q_e = 1 + \frac{0.006}{1.082} = 1.006 \quad \text{(Eqs. 18–19)}$$

$\epsilon_r =$ (Table V); $E = 69/\sqrt{3} = 40$;
$\cos\phi = 0.005$

$$W_d = \frac{0.00276(40)^2(3.5)(0.005)}{\log \frac{2.113}{1.543}}$$
$= 0.57$ watt per conductor foot (Eq. 36)

$\rho_i = 550$ (Table VI);

$$\bar{R}_i = 0.012\left(550 \log \frac{2.113}{1.543}\right)$$

$= 0.90$ thermal ohm-foot (Eq. 38)

$n' = 1$; $\bar{R}_{sd} = \frac{1(4.6)}{2.37+0.27} = 1.74$ thermal ohm-feet (Eq. 41A)

$\rho_d = 480$ (Table VI); $t = 0.25$; $D_e = 5.0+0.5 = 5.50$ for fiber duct

$\bar{R}_d = \frac{0.0104(480)(0.25)}{5.50-0.25} = 0.24$ thermal ohm-foot (Eq. 40)

RHO-120

$\rho_c = 120$ (asumed); $\rho_e = 85$ (Table VI); $L = L_b = 43.5$ inches (Fig. 3)

$N = 6$; $(LF) = 0.80$ (assumed);

$$F = \left(\frac{96}{9}\right)\left(\frac{78}{9}\right)\left(\frac{96.5}{12.7}\right)\left(\frac{87.5}{9}\right)\left(\frac{78.5}{12.7}\right)$$

$= 42{,}200$ (Fig. 3 and Eq. 46)

$L_b/P = \frac{43.5}{2(18+27)} = 0.483$; $\frac{27}{18} = 1.5$; $G_b = 0.87$ (Fig. 2)

$\bar{R}_e'$ (at 80% loss factor) $= (0.012)(85)(1)\times$

$$\left(\log\frac{8.3}{5.5} + 0.80\log\left[\frac{4(43.5)}{8.3}(42{,}200)\right]\right) + 0.012(120-85)(1)(6)(0.80)(0.87)$$

$= 6.79$ thermal ohm-feet (Eq. 44A)

$\bar{R}_e'$ (at unity loss factor) $= 8.44$ thermal ohm-feet (Eq. 44A)

$\bar{R}_{ca}' = 0.90 + 1.006(1.74+0.24+6.79)$

$= 9.72$ thermal ohm-feet (Eq. 8)

$$\Delta T_d = 0.57\left(\frac{0.90}{2}+1.74+0.24+8.44\right)$$

$= 6.2$ C (Eq. 6)

$T_a = 25$ C (assumed);

$$I = \sqrt{\frac{75-(25+6.2)}{8.60(1.082)(9.72)}}$$

$= 0.696$ kiloampere (Eq. 9)

To illustrate the case where the cable circuits are not identical, consider the second circuit to have 750-MCM conductors. For the first circuit,

$N = 3$; $(LF) = 0.80$ (assumed);

$$F = \left(\frac{96}{9}\right)\left(\frac{78}{9}\right) = 92.4 \quad \text{(Eq. 46)}$$

$\bar{R}_e' = 0.012(85)\cancel{(1)}\times$

$$\left[\log\frac{8.3}{5.5} + 0.80\log\left(\frac{4(43.5)}{8.3}\,92.4\right)\right] + 0.012(120-85)(1)(3)(0.80)(0.87)$$

$= 3.74$ thermal ohm-feet (Eq. 44A)

$$F_{int} = \left(\frac{96.4}{12.7}\right)\left(\frac{87.5}{9}\right)\left(\frac{78.5}{12.7}\right) = 456$$

(Eq. 50)

$\bar{R}_{int} = 0.012(1)\times$

$[85 \log 456 + 3(120-85)(0.87)]$

$= 3.81$ thermal ohm-feet (Eq. 49)

$\bar{R}_{ca}' = 0.90 + 1.006(1.74+0.24+3.74)$

$= 6.65$ thermal ohm-feet (Eq. 8)

$\Delta T_d = 0.57(0.45+1.75+0.24+4.63) = 4.0$ C (Eq. 6)

$W_c = (I_1^2)(8.60)(1.082) = 9.31 I_1^2$ watts per conductor foot (Eq. 15)

$\Delta T_{int} = (9.31 I_1^2[(1.006)(0.80)+0.57])3.81$

$= 2.17 + 28.5 I_1^2$ degrees centigrade in circuit no. 2 (Eq. 48)

Similar calculations for the second circuit yield the following values.

$\bar{R}_{ca}' = 7.18$; $\Delta T_d = 3.4$; $W_{c2} = 17.44 I_2^2$; $\Delta T_{int} = 1.71 + 53.2 I_2^2$ in circuit no. 1

$$I_1^2 = \frac{75-(25+4.0+1.71+53.2I_2^2)}{(9.31)(6.65)}$$

$= 0.715 - 0.859 I_2^2$ (Eq. 9A)

$$I_2^2 = \frac{75-(25+3.4+2.17+28.5I_1^2)}{(17.44)(7.18)}$$

$= 0.355 - 0.228 I_1^2$ (Eq. 9A)

Solving simultaneously $I_1 = 0.714$; $I_2 = 0.487$ kiloampere.

138-Kv 2,000-MCM High-Pressure Oil-Filled Pipe-Type Cable 8.625-Inch-Outside-Diameter Pipe

The cable shielding will consist of an intercalated 7/8(0.003)-inch bronze tape—1-inch lay, and a single 0.1(0.2)-inch D-shaped brass skid wire—1.5-inch lay. The cables will lie in cradled configuration.

$D_c = 1.632$; $D_i = 2.642$; $T = 0.505$; $D_s = 2.661$; $D_p = 8.125$

$$T_c = 70 \text{ C};\ R_{dc} = \left(\frac{12.9}{2.00}\right)\left(\frac{234.5+70}{234.5+75}\right)$$

$= 6.35$ microhms per foot (Eq. 10A)

For shielding tape $A_s = 7/8(0.003) = 0.00263$; $l = 1.0$; $\rho = 23.8$; $r = 564$ (Table I)

$$R_s = \frac{23.8\pi}{4(0.00263)}\sqrt{1+\left(\frac{2.66\pi}{1}\right)^2}\times\left(\frac{564+50}{564+20}\right) = 62{,}900 \text{ microhms}$$

per foot at 50 C (Eq. 13)

For skid wire $A_s = \frac{1}{2}\pi(0.1)^2 = 0.0157$;

$l = 1.5$; $\rho = 38$; $r = 912$ (Table I)

$$R_s = \frac{38\pi}{4(0.0157)}\sqrt{1+\left(\frac{2.66\pi}{1.5}\right)^2}\times\left(\frac{912+50}{912+20}\right) = 11{,}100 \text{ microhms}$$

per foot at 50 C (Eq. 13)

$$R_s\,(\text{net}) = \left[\frac{(62.9)(11.1)}{(62.9)+(11.1)}\right]1{,}000$$

$= 9{,}435$ microhms per foot at 50 C

$k_s = 0.435$; $k_p = 0.37$ (Table II)

$R_{dc}/k_s = 14.6$; $Y_{cs} = 0.052(1.7) = 0.088$ (Eq. 21, Fig. 1, and text)

$S = 2.66+0.10 = 2.76$; $R_{dc}/k_p = 17.2$; $F(x_p') = 0.035$ (Fig. 1)

$$Y_{cp} = 4\left(\frac{1.632}{2.76}\right)^2(0.035)(1.7) = 0.083$$

(Eq. 24A and text)

$1 + Y_c = 1 + 0.088 + 0.083 = 1.171$

$$X_m = 52.9\log\frac{(2.3)(2.76)}{2.66}$$

$= 20.0$ microhms per foot (Eq. 29A)

$$Y_s = Y_{sc} = \frac{(20.0)^2(1.7)}{(9.435)(6.35)} = 0.011$$

(Eq. 27A and text)

$$Y_p = \frac{(0.34)(2.76)+(0.175)(8.13)}{6.35} = 0.372$$

(Eq. 35)

$R_{ac}/R_{dc} = 1.171 + 0.011 + 0.372 = 1.554$ (Eq. 14)

$q_s = 1 + \frac{0.011}{1.171} = 1.009$; $q = 1 + \frac{0.011+0.372}{1.171}$

$= 1.327$ (Eqs. 18–19)

$\epsilon_r = 3.5$ (Table V); $E = 138/\sqrt{3} = 80$; $\cos\phi = 0.005$

$$W_d = \frac{0.00276(80)^2(3.5)(0.005)}{\log\frac{2.642}{1.632}}$$

$= 1.48$ watts per conductor foot (Eq. 36)

$\rho_i = 550$ (Table VI); $\bar{R}_i = 0.012\times$

$\left(550 \log\frac{2.642}{1.632}\right) = 1.38$ thermal ohm-feet (Eq. 38)

$n' = 3$; $D_s' = 2.15(2.66) = 5.72$;

$R_{sd} = \frac{3(2.1)}{5.72+2.45} = 0.77$ thermal ohm-foot (Eq. 41A)

$\rho_d = 100$ (Table VI); $t = 0.50$; $D_e = 8.63+1.0 = 9.63$ for 1/2-inch wall of asphalt mastic

$$\bar{R}_d = \frac{0.0104(100)(3)(0.50)}{9.63-0.50}$$

$= 0.17$ thermal ohm-foot (Eq. 40)

Assume $\rho_e = 80$, $L = 36$ inches, $(LF) = 0.85$; $N = 1$, $F = 1$

$\bar{R}_e'$ (at 85% loss factor) $= 0.012(80)(3)\times$

$$\left[\log\frac{8.3}{9.63} + 0.85\log\left(\frac{4(36)}{8.3}(1)\right)\right]$$

$= 2.85$ thermal ohm-feet (Eq. 44)

$\bar{R}_e'$ (at unity loss factor) $= 3.38$ thermal ohm-feet (Eq. 44)

$\bar{R}_{ca}' = 1.38 + 1.009(0.77) + 1.327(0.17+2.85)$

$= 6.17$ thermal ohm-feet (Eq. 8)

$\Delta T_d = 1.48(0.69+0.77+0.17+3.38) = 7.4$ C (Eq. 6)

$T_a = 25$ C (assumed);

$$I = \sqrt{\frac{70-(25+7.4)}{(6.35)(1.171)(6.17)}}$$

$= 0.905$ kiloampere (Eq. 9)

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Discussion

C. C. Barnes (Central Electricity Authority, London, England): This paper is an excellent and up-to-date study of a most important subject. For 25 years D. M. Simmons' articles have been used for fundamental study on current rating problems, but the numerous cable developments and changes in installation techniques introduced in recent years have made a modern assessment of this subject very necessary. The essential duty of a power cable is that it should transmit the maximum current (or power) for specified installation conditions. There are three main factors which determine the safe continuous current that a cable will carry.

1. The maximum permissible temperature at which its components may be operated with a reasonable factor of safety.

2. The heat-dissipating properties of the cable.

3. The installation conditions and ambient conditions obtaining.

In Great Britain the basic reference document is ERA (The British Electrical and Allied Industries Research Association) report *F/T131*[1] published in 1939, and in 1955 revised current rating tables for solid-type cables up to and including 33 kv were published in ERA report *F/T183*. A more detailed report summarizing the method of computing current ratings for solid-type, oil-filled, and gas-pressure cables is now being finalized and will be published as ERA report *F/T187* some time in 1958.

Until recent years current ratings in eat Britain have usually been considered on a continuous basis, but the importance of taking into consideration cyclic ratings has now been carefully studied, since continued high metal prices have forced cable users to review carefully the effects of cyclic loadings. A report has recently been issued in which a simple method is presented for the rapid calculation of cyclic ratings.[2]

Table V gives specific inductive capacitance values for paper as: paper insulation (solid type), 3.7 (IPCEA value); paper insulation (other type), 3.3–4.2. Is it possible to list the other types and their appropriate specific inductive capacitance values or alternatively simply use an average specific inductive capacitance value of 3.7, for example, for all types of paper insulation?

Reference is made to the adoption of the hypothesis suggested by Kennelly as the basis of the paper—this is a logical approach but it appears to differ from the basis of computing ratings hitherto adopted in the United States. An amplification of the authors' viewpoint on this important issue will be welcomed.

With reference to the use of low-resistivity backfill, recent studies in Great Britain have shown that the method of backfilling cable trenches deserves careful consideration as attention to this point can result in increases up to 20% in load currents.

Equation 43 gives the thermal resistance between any point in the earth surrounding a buried cable and ambient earth. It is

Table X. Temperature Limits* for Belted-, Screened- and HSL†-Type Cables

System Voltage and Type of Cable	Laid Direct or in Air: Lead Sheathed, Armored	Laid Direct or in Air: Lead Sheathed, Unarmored	Laid Direct or in Air: Aluminum Sheathed, Armoured or Unarmored	In Ducts: Lead Sheathed, Armored	In Ducts: Lead Sheathed, Unarmored	In Ducts: Aluminum Sheathed, Armored or Unarmored
1.1 kv						
Single-core		80	80		60	80
Twin and multicore belted	80	80	80	80	60	80
3.3 kv and 6.6 kv						
Single-core		80	80		60	80
Three-core belted-type	80	80	80	80	60	80
11 kv						
Single-core		70	70		50	70
Three-core belted-type	65	65	65	65	50	65
Three-core screened-type	70	70	70	70	50	70
22 kv						
Single-core		65	65		50	65
Three-core belted-type	55	55		55	50	
Three-core screened-type	65	65	65	65	50	65
Three-core (SL‡ or SA§)	65		65	65		65
33 kv (screened)						
Single-core		65			50	
Three-core	65	65		65	50	
Three-core HSL	65			65		

* Measured in degrees centigrade.
† Hochstater separate lead.
‡ Separate lead sheathed.
§ Separate aluminum sheathed.

not clear, however, what value of soil thermal resistivity is used in this expression and information on this important point is desirable.

In Great Britain a value of soil thermal resistivity (g) of 120 C cm/watt is generally used but further test data are being slowly acquired, and where tests have indicated that a lower value, e.g., 90 C cm/watt, is justified, this value is used. Current loading tables in ERA report *F/T183* provide data for soil thermal resistivity values of 90 and 120 C cm/watt, and correction factors for other values of soil thermal resistivity are also provided.

In the United States buried cables are usually pulled into duct banks, but there must be many cases where direct burial, as normally used in Great Britain, will result in lower installation costs. Formulas dealing with this installation technique are a desirable addition. Permissible temperature limits for the various types of cables and installation conditions used in the United States will be a helpful appendix, and it is suggested that this information should be added to the paper. For comparison purposes, the limits recommended in Great Britain are summarized in Table X and in the following:

Plastic-insulated power cables............
70 C maximum conductor temperature

Gas-pressure and oil-filled cable systems (all types)........................
85 C maximum conductor temperature

Finally, it will be helpful to know if adoption of the formulas in the paper will necessitate revision or amplification of existing rating tables and, if so, when the revised tables will be published.

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2. THE CALCULATION OF CYCLIC RATING FACTORS FOR CABLES LAID DIRECT OR IN DUCTS, H. Goldenberg. *Proceedings*, Institution of Electrical Engineers, London, England, vol. 104, pt. C, 1957, p. 154.

H. Goldenberg (Electrical Research Association, Leatherhead, England): The calculation of cable ratings is a subject of prime importance to cable engineers. Nevertheless, it seems that until recently the American standard work on this subject has been that of Simmons,[1] while the corresponding British standard work has been recorded by Whitehead and Hutchings.[2] These papers have been supplemented by scattered published papers, including developments dealing with cyclic loading.

The paper by Mr. Neher and Mr. McGrath records up to date American cable-rating practice in a manner that will prove invaluable to engineers for many years to come. It is a pleasing feature that the authors are especially competent to deal with this subject in view of their valuable contributions to the cable-rating field over a number of years. Modern British cable rating practice has recently been recorded in an ERA report[3] dealing with continuous current ratings, and in two IEE (Institution of Electrical Engineers) papers[4,5] (based on ERA reports) dealing with cyclic loading, but the majority of this work is in process of printing and publication.

An obvious difference in British and American technique is the method of cyclic rating factor calculation. Mr. Neher and Mr. McGrath's method is based on an equivalence between typical daily loss cycles and sinusoidal loss cycles of the same loss factor, while a method recently introduced in Britain[4,5] takes full account of the form of a daily load cycle. Both methods are considerably shorter than any that have been available hitherto. Nevertheless, without further study I would not feel certain that for British-type cables, subject to their typical daily cycles, the form of the cyclic load can be adequately taken into account by use of the loss factor independently of the cyclic load wave form giving rise to it. In fact the conclusion reached in my second IEE paper,[5] is that a knowledge of the cyclic load wave form for the 6 hours prior to peak conductor temperature, together with the loss factor, are adequate for cyclic rating factor calculation. However, it would be unfair to assess any of the relative merits of the two methods prior to the publication of one of them.

The difference between British and American cable rating technique is not so marked for continuous current rating calculation as might appear to be the case at first sight. In fact, such differences as exist are principally due to the different types of cables employed on each side of the Atlantic, and to the different standard a-c frequencies in use. Nevertheless a comparison of the present paper with the ERA report dealing with continuous current ratings[3] gives rise to certain observations.

The present paper is principally directed to the calculation of a single current rating, but one use to which it might well be put is the large-scale preparation of current rating tables, with rating factors for non-standard conditions. For such an application it is often preferable to introduce explicit formulas for the rating factors, as these formulas might be independent of some of the thermal resistances or loss factors involved, with a consequent saving in calculation time.

The method employed for external thermal resistance calculation for grouped cables laid direct in the ground differs somewhat from that recommended in a recent paper of mine.[6] For the preparation of group rating factors for the more commonly occurring groups of cables dealt with in an ERA report,[7] the combination of certain simplified external thermal resistance formulas and my recommended method has led to a substantial saving in calculation time. I do not favor the introduction of a geometric-mean distance, or its equivalent, as it is inconvenient for unequally loaded cables.

A brief résumé of other points is that the thermal resistivity values given in Table VI for thermal resistance calculation are generally somewhat lower than the corresponding British values, that the proximity effect on cylindrical hollow conductors appears to me to be best obtained from Arnold's paper,[8] that where sheath and nonferrous reinforcement losses occur a parallel combination of sheath and reinforcement resistance permits the calculation of a single loss factor, that a simple formula has been derived for the external thermal resistance of one of three cables in trefoil touching formation laid direct in the ground,[6] and that sector correction factors are often used in British practice for 3-core cable rating calculations.

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Elwood A. Church (Boston Edison Company, Boston, Mass.): The authors present a large amount of useful data and formulas for the calculation of cable thermal constants and suggest a new approach to the problem of calculation of temperature rise for various loss factors including steady-load or 100% loss factor. Cable engineers usually agree on the factors to be taken into account and the methods of calculation for steady loads. However, there appears still to be disagreement on the problem of cyclic loading.

At the AIEE General Meeting in January 1953, a group of papers[1] was presented suggesting various approaches to the problems of cyclic loading on buried cables and on pipe-type cable. Of the methods suggested in these papers, the one which appealed to the author the most was Mr. Neher's method using sinusoidal loss cycles. In his paper it was shown that this method yields reasonably accurate results for the higher loss factors. For a low loss factor sharply peaked cycle, the results are not as accurate.

A modification of this method would be to represent the load cycle more accurately by splitting it into harmonics and computing the temperature rise for each harmonic separately. This entails more work, but with modern methods of machine calculation it is economical to use the most accurate method available and let the machine perform the laborious calculations. In fact, it takes very little more time on the machine when the more rigorous methods are used instead of any of the approximate methods which have been suggested.

The author has investigated the various methods of calculation of the cyclic component of temperature rise of 1,250-MCM

Table XI. Thermal Impedance Functions

1,250-MCM 115-Kv Cable Enclosed in 6¹/₄-Inch-Outside-Diameter Pipe

Harmonic	T_1/Q_0	T_2/Q_0	T_3/Q_0	T_4/Q_0
0*	$8.03\angle 0°$	$6.55\angle 0°$	$5.97\angle 0°$	$5.50\angle 0°$
0†	$10.56\angle 0°$	$9.08\angle 0°$	$8.50\angle 0°$	$8.03\angle 0°$
1	$2.88\angle -30°$	$1.67\angle -43°$	$1.24\angle -54°$	$0.93\angle -61°$
2	$2.29\angle -38°$	$1.19\angle -54°$	$0.82\angle -68°$	$0.57\angle -77°$
3	$1.94\angle -43°$	$0.94\angle -61°$	$0.61\angle -79°$	$0.39\angle -87°$
4	$1.68\angle -50°$	$0.76\angle -67°$	$0.48\angle -87°$	$0.29\angle -95°$

* Steady-state component for single pipe.

† Steady-state component for two pipes, 18 inches apart.

Q_0 = watts copper loss per conductor per foot
T_1 = temperature rise of conductor
T_2 = temperature rise of shielding tape
T_3 = temperature rise of oil in pipe
T_4 = temperature rise of pipe

Table XIII. Maximum Temperature Rise for Cyclic Loading

Method of Calculation	Conductor Temperature, C: 1 Pipe	Conductor Temperature, C: 2 Pipes	Pipe Temperature, C: 1 Pipe	Pipe Temperature, C: 2 Pipes
For Loss Cycle 1				
1	39.1	49.2	24.1	34.3
2	39.8	49.9	24.6	34.8
3	39.9	50.1	23.2*	33.4*
For Loss Cycle 2				
1	30.9	37.5	17.1	23.8
2	32.6	39.2	18.2	24.9
3	32.8	39.5	16.1*	22.8*

These figures do not include the temperature rise due to dielectric loss, which would be added to the steady-state component.

* These are average temperatures. It is not possible to compute the maximum temperature of the pipe by this method.

115-kv cables enclosed in 6¹/₄-inch-outside-diameter pipe buried in the earth. The results of three such methods for two representative load cycles are presented in this discussion for comparison. The three methods compared are: (1) the Harmonic method using Bessel functions to compute the heat-flow constants of the cable for each harmonic of the temperature cycle, (2) the sinusoidal method suggested by Mr. Neher in his 1953 paper, and (3) the latest method suggested by Mr. Neher and Mr. McGrath in their current paper. Space in this discussion does not permit a complete derivation of the heat-flow equations for the harmonic components of the heat-flow cycle, but only the results, as calculated by an IBM (International Business Machines) *650*, are tabulated in Table XI. It may be noted that the machine time to solve the eight simultaneous equations necessary for the solution of the temperatures and heat flows for each harmonic was approximately 5 minutes per matrix, with a separate solution necessary for each harmonic. The whole cost of the job in rental time on the machine and punching the data on the cards for insertion in the machine was $150 for three different sizes of cable (a total of 12 matrixes). The cost of programming was small since the general program for solution of complex simultaneous equations was already available in the IBM library, and only a small amount of work was necessary to set up this particular problem.

Table XII. Harmonic Components of Loss Cycles

Harmonic	Loss Cycle 1: Loss, Watts	Loss Cycle 1: Phase Angle, Degrees	Loss Cycle 2: Loss, Watts	Loss Cycle 2: Phase Angle, Degrees
0	4.03		2.64	
1	2.50	0	2.31	− 20
2	1.10	+30	0.43	+185
3	0.20	−90	0.60	+ 65
4	0.53	+40	0.53	− 35

Example: The equation of loss cycle 1 using the foregoing data is as follows: (Maximum $Q_0 = 6.6$ watts per foot per conductor)

$$Q_0 = 4.03 + 2.50 \sin \omega t + 1.10 \sin (2\omega t + 30°) + 0.20 \sin (3\omega t - 90°) + 0.53 \sin (4\omega t + 40°) \text{ watts}$$

Corresponding temperature cycle for conductor temperature is as follows for a single pipe: (Maximum $T_1 = 39.1°$)

$$T_1 = 32.4 + 7.24 \sin (\omega t - 30°) + 2.57 \sin (2\omega t - 8°) + 0.39 \sin (3\omega t - 133°) + 0.89 \sin (4\omega t - 7°)$$ degrees centigrade

Zero time = 9.00 a.m. in the foregoing expressions.

The components of the loss cycles with which the data in Table XI was multiplied to obtain the temperature cycles are given in Table XII. These loss cycles are illustrated in Figs. 4 and 5, with the corresponding temperature cycles of the conductor and pipe.

In all future calculations of this sort, it is planned to carry the programming still further and have the machine calculate the temperature cycle for each size of cable and determine its maximum value. This has been estimated to cost approximately $500 for programming and $15 extra per size of cable to compute.

Usually only the temperature of the conductor and the pipe are significant in calculation of the current-carrying capability but the electronic calculator automatically computes the other values listed in Table XI, and they are recorded for whatever use may be made of them.

A tabulation of maximum temperatures for the foregoing two load cycles and the three different methods of calculation listed previously are tabulated in Table XIII in the same order. Examination of this table will reveal that the sinusoidal method yields results which are nearer to the more accurate harmonic method than the latest method proposed in the paper. The agreement between the various methods is seen to be better at the higher loss factors.

It may be argued that the agreement is close enough between the three methods for all practical purposes and that the accuracy of the original thermal constants from which the computations were made does not warrant the extra work necessary to use the harmonic method. However, the danger in using an approximate method is that someone unfamiliar with its derivation and its limitations will use it where it does not apply. The author does not consider the agreement close enough for 40% loss factor.

The computation of the pipe temperature is just as important as the conductor temperatures, especially in summer when high earth temperatures prevail and where higher daily loss factors are more likely to be encountered. If the earth next to the pipe exceeds an average of 50 C, there is danger of drying out the soil causing thermal instability. Calculations of current-carrying capability should take this limit into account.

Reference

1. See reference 3 of the paper.

R. J. Wiseman (The Okonite Company, Passaic, N. J.): The authors are to be commended for this very fine technical paper. The need for an up-to-date compilation of engineering formulas and constants for the calculation of current-carrying capacities of cables has been of increasing importance every year. When Dr. Simmons wrote his series of papers about 25 years ago we might say the electrical cable industry was young in engineering knowledge, the types of cable furnished were not too great in number, and the characteristics of the cables were not too well known. Today our knowledge of cable design, materials, and operating conditions along with new types of cables is far in advance of 25 years ago. We have been using the formulas as they became known and it was desirable to bring them together in one place and, in addition, all of us who have occasion to make these calculations will be using the same formulas and electrical and thermal constants. Also, this paper will be of great help to younger men coming into the cable industry. Although it summarizes the formulas, anyone wishing to get a clearer appreciation of the text can refer to the bibliography and study the original papers.

To make any text of this kind generally useful, it is desirable that the procedure be easy to follow and the formulas readily applied. Theoretical formulas involving higher mathematics can be used, but they take time, and very often it is not possible to take the time to work up a case. Again conditions of installation are variable daily, so if we attempt to make a field check of calculations we can find differences; therefore, exactness to a high degree is

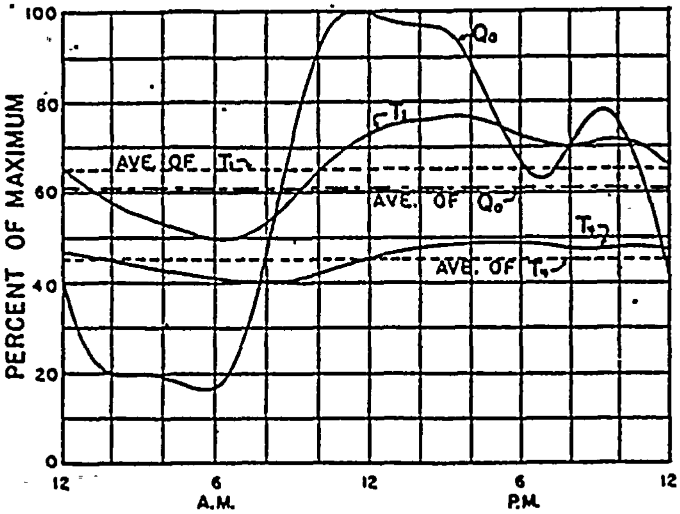

Fig. 4. Loss and temperature cycles for 75% load factor, summer load cycle

Q_0 = copper loss cycle
T_1 = temperature of conductor
T_4 = temperature of pipe

Temperatures are in per cent of copper temperature corresponding to steady load equal to the maximum.

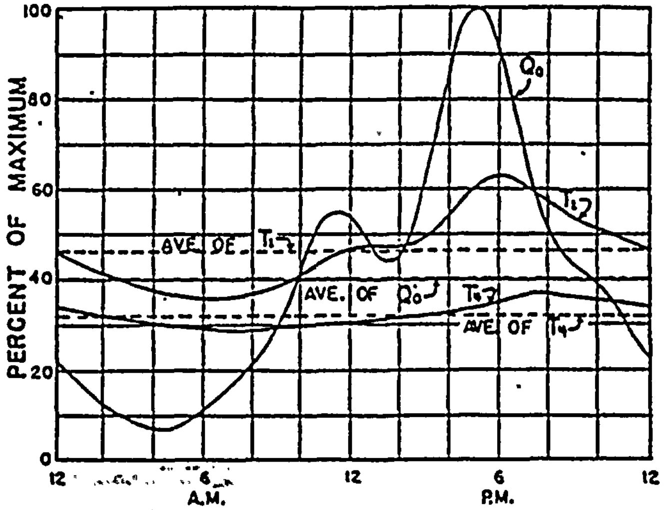

Fig. 5. Loss and temperature cycles for 60% load factor winter load cycle

Values same as in Fig. 4

not necessary. It has been suggested that it is now possible to use computers on these problems. This is true for those who have a computer, but here also time is taken for setting up the problem for the computer. Also we must show how to calculate the currents and in a form that will be used.

You will note that many of the formulas are new to most of you. These formulas were developed to make the calculations easily and quickly and yet do not cause a large error in the final answer from the highly theoretical formula. It is natural that the formulas may be a compromise and some may feel that a particular formula that they use may be superior to that recommended. Likewise the thermal constants may be a compromise. This is true as far as I am concerned, yet we are willing to accept the recommendations given in the paper. The calculation of the various losses existing in a cable system and the location of these losses is well done and should be carefully studied by all new engineers.

The section dealing with the calculation of some of the thermal resistances need careful study in order to appreciate them as they depart from the usual manner in which a thermal resistances are calculated. For example: the thermal resistance between a cable and a surrounding wall, such as a duct wall or a pipe; see equations 41 and 41(A). Heretofore, we used $\bar{R}_{sd} = 0.00411\ B/D$, and referred to as the IPCEA method. This has been revised to take into consideration the condition existing and the materials. Equation 41(A) is a general one, and by inserting the correct values of A' and B' as given in Table I, we can get R_i. This is an example of how we can accept a compromise in order to get agreement. We at Okonite made tests years ago to determine the thermal constants for the oil or gas medium surrounding cables in a pipe. We tried to use the cylindrical log formula and found the apparent thermal resistivity varied due to the convection effects of the oil. If we took the simple formula $R_{sd} = 1.60/D$ where D is the diameter over the shielding tape we found we got good agreement with test. We neglected temperature effects as the actual value of R_{sd} as compared to the thermal resistance of the insulation is very low, many times in the order of one-tenth; therefore, temperature effects are small. For a gas medium using 200 pounds per square inch we use the equation $\bar{R}_{sd} = 2.58/D$. How do these formulae compare with equation 41(A) proposed by the authors?

Consider two cases, one having a diameter over the shielding tape of 1 inch and another having a diameter of 2.5 inches. The following table compares the two types of equations.

Medium		Diameter = 1 Inch, Thermal Ohm-Foot	Diameter = 2.5 Inches, Thermal Ohm-Foot
Oil	Okonite	1.60 t.o.f.	0.64 t.o.f.
	Neher and McGrath	1.37	0.80
Gas	Okonite	2.58 t.o.f.	1.03 t.o.f.
	Neher and McGrath	2.22	1.04

The differences are not great and when considered in relation to the total thermal resistance, they are negligible. We can accept the authors' equations.

I am glad to see the authors place the duct system in proper relationship to a buried cable system and that the same soil thermal resistivity will be used when making comparisons. This was the weakness in the duct heating constants originally set up by NELA and later known as IPCEA constants. Also a better understanding of the effect of multiple cables in a duct bank is obtainable, and the determination of the cable having the highest thermal resistance is possible.

Appendix III discusses the derivation of D_x, a fictitious diameter in the soil up to which it is assumed that a steady heat load exists and outside which the loss factor of the load is taken into consideration. I have not been able to accept this assumption. It is an endeavor to obtain a thermal resistance for the soil that will check with a study that Messrs. Neher, Buller, Shanklin and myself made and is referred to in reference 3 in the bibliography of this paper. A study of the previous papers will show that the attainment factor is not exactly the same for all types of cables studied and all shapes of load curves.

The authors tabulate in Table IX a comparison of the attainment factor for three methods of calculation for a loss factor of 30% for several cable designs. Rather than give results for one loss factor only, it would have been better if they had covered the range of loss factors which were studied in 1953. If these attainment factors were plotted against loss factor as I did in my paper, it would have been noted that a straight line could be drawn giving a good representation of how (AF) varies with loss factor, namely, $(AF) = 0.43 + 0.57\ (lf)$ for my method. This equation follows the plot of (AF) and loss factor very well down to about 35% loss factor, and in some cases, it gave a higher value and other cases a lower value than actually calculated. The (AF) values I reported are based on careful calculations from the exact load curve and no assumption that a single sine-wave curve can be taken as representing any load curve. As it is a rarity that cables are designed for loss factors as low as 30% (50% load factor), my formula gives results as accurate as when using D_x and easier to use. However, for the sake of uniformity in methods of calculation, we will accept the authors' method.

In this connection, I would like to raise a question which I hope will be taken up by others interested in this subject. The use of the equation involving D_x is an

attempt to increase the thermal resistance for the soil for cables or small pipe sizes; in other words, the computed value of thermal resistance is too low. Is it not likely that we are leaving out of our equation a term involving a surface contact between the surface of the cable or pipe and the soil. This term would be of the same form as we now use for the case of cables in air, namely, $\bar{R}=0.00411\ B/D$. If we add this term to the log formula for soil thermal resistance, we will get a higher total resistance and the influence of the diameter of the cable or pipe will be greater, the lower the diameter. It will be necessary to determine the value of B. The idea of such a term is shown in the paper[1] by Mr. Mather and his coauthors. In Table I they give some thermal data obtained from tests made by them on a pipe-type cable. They give a value of B for surface of Somastic to water of 218 thermal ohms per cm². I like this. Is it not likely that we have a surface resistivity between the cable and the soil in immediate contact?

REFERENCE

1. BONNEVILLE POWER ADMINISTRATION HIGH-VOLTAGE CABLE STUDIES, R. J. Mather, F. J. McCanna, E. Demirjian. *AIEE Transactions*, vol. 76, pt. III, 1957 (*Paper no. 57-739*).

E. R. Thomas (Consolidated Edison Company of New York, Inc., New York, N. Y.): The authors are to be congratulated in setting up mathematical equations to evaluate load carrying capabilities of cable systems. I regret that no mention was made of the pioneer work by Wallace B. Kirke in the middle 1920's on the rating of cables installed in duct banks. This work, I believe, furnished the basis of cable rating of the NELA and present IPCEA published ratings of cable. The work of Kirke was presented before the AIEE and published in the Journal.[1]

The work on ratings of cable by Kirke was based on thousands of field measurements in the New York City area and later field measurements furnished by utilities throughout the country furnished data which lead to the NELA-IPCEA rating value. This was done before the general use of pipe-type cable. It should be obvious that the answer obtained by mathematical solution is never any better than the assumptions on which the equations are developed and the constants used with the equations.

I believe the actual heat flow in underground cable systems is considerably more complex than has been assumed in this paper and, therefore, actual ratings which are obtained may be different from those obtained by this calculation.

REFERENCE

1. THE CALCULATION OF CABLE TEMPERATURES IN SUBWAY DUCTS, Wallace B. Kirke. *AIEE Journal*, vol. 49, Oct. 1930, pp. 855–59.

H. D. Short (Canada Wire and Cable Company, Toronto, Ont., Canada): Several of the engineers who work with me at Canada Wire have been studying the Neher-McGrath paper over the past few months, and have arrived at certain conclusions, some of which are discussed in the following paragraph.

The determination of the losses in the conductor, shield, sheath or pipe, and the dielectric have been well established by the authors and bear no further comment. The calculation of the thermal resistances of direct buried cable and pipe-cable installations appear to have been well founded; although the method of arriving at the effect of cyclic loading seems to be in question amongst the various investigators (reference 3 of the paper). However, as far as duct bank installations are concerned, the difference between the NELA or IPCEA current rating method and that proposed by the authors is so great that one cannot help but wonder at the dearth of practical data in the paper.

In reading references 10, 12, 13, 16, and 17 of the paper, there seems to be very little data on cable temperature measurements taken in the field, such as was done by the various utilities when the NELA values were established. The work reported in these references is almost all theoretical, and laboratory measurements and analogue methods used are all approximations.

I am given to understand that there is a movement afoot to have this Neher-McGrath method accepted and to revise the IPCEA current rating tables accordingly. I am not sure that this is the case—but if it is, then perhaps the authors can tell us upon what factual data their method is based.

We have used the method given in the paper to compute the current rating of quite a number of high-voltage cable circuits in a duct bank and find complete disagreement with the NELA or IPCEA method. In every case the Neher-McGrath method results in a larger conductor size for a given current rating, in some cases as much as 30% more conductor metal is required by the Neher-McGrath method.

Here is where our dilemma begins. One of two things prevails: either Mr. Neher and Mr. McGrath have cornered the nonferrous metal market or they are attempting to make a pipe-type cable carry the same load as a duct-bank installation. Yet on the face of it, it is incomprehensible how anyone can conceive of a 3-conductor high-voltage cable (and a pipe-type cable is in fact a direct-buried 3-conductor cable) competing on a current rating basis with single-conductor high-voltage cables separately spaced in a duct bank where a-c losses are a minimum and heat dissipation a maximum. In either event we cannot understand why so much time should be spent on developing a new method of current rating calculation for duct-bank systems without first having at least obtained some actual in-service field measurements to substantiate their formulas.

On the other hand, we must sincerely commend the authors for attempting to arrive at a realistic comparison between duct-bank and direct-buried systems. It is unfortunate, however, that in doing so they have not based their formula development on extensive field survey data as was done at the time the NELA duct constants were established.

The only way in which we have as yet been able to make the Neher-McGrath method track with the old and well proved NELA method is to reduce the soil thermal resistivity to the order of 40 C to 75 C cm/watt. The actual value which one would use to arrive at the same conductor size as determined by the NELA method appears to depend upon the number of cables in the duct bank and the value of the daily load factor chosen. In contradistinction, Mr. Neher in reference 13 of the paper states that his method agrees within 10% of the NELA method if a $\rho_e=75$ C cm watt is used.

We have made some calculations of the thermal resistance of cables in a duct bank from the sheath to ground (or sink) using the Neher-McGrath method and the average conditions on which the NELA duct constants were obtained. The average conditions were:

1. Most of the measurements were taken under paved streets with the depth of pavement between 10 and 12 inches.
2. Majority of ducts were made of fibre.
3. Average duct inner diameter = 3.75 inches.
4. Concrete spacer between ducts 2 inches, with duct wall = 1/4-inch, 3-inch outer concrete shell. Spacing between duct centres = 6¼ inches.
5. Average depth of burial to top of duct bank = 30 inches.
6. Most measurements with 3-conductor lead sheathed cables from 2 inches to 3 inches outside diameter. Average diameter 2.5 inches.
7. All loaded cables in outside ducts, all equally loaded.
8. Soil thermal resistivity (*in situ*) = 120 C cm/watt.

Two cases were studied and the results are summarized in the following:

Case I—Three cables in 2 by 2 duct bank (one of lower ducts empty).

NELA Value (i.e. $4.93/D_s'+L_f NH$)
Loss factor........100%..62.5%..33%
Rth_{S-A} thermal/ohms-feet.......5.09 ..3.92 ..3.00

Neher-McGrath Value
Loss factor........100%..62.5%..33%
Upper cables
Rth_{S-A} thermal/ohms-feet......6.68 ..5.02 ..3.71
Lower cable
Rth_{S-A}..........6.63 ..4.99 ..3.70
Average values....6.66 ..5.01 ..3.71

In order for Neher-McGrath values of thermal resistances to be equal to NELA values, soil resistivity would have to be:

At 100% loss factor $\rho_e=65$ C cm/watt
At 62.5% loss factor $\rho_e=60$ C cm/watt
At 33.0% loss factor $\rho_e=45$ C cm/watt

Case II—Six cables in 2 wide by 3 deep duct bank.

NELA Value
Loss factor......100%..62.5%..33.0%
Rth_{S-A} thermal/ohms-feet....6.89 ..5.05%..3.60

Neher-McGrath Value
Loss factor......100%..62.5%..33.0%

Upper layer $Rth_{5\text{-}4}$ thermal/ohms-feet	10.23	7.24	4.88
Middle layer $Rth_{5\text{-}4}$ thermal/ohms-feet	10.95	7.69	5.12
Lower layer $Rth_{5\text{-}4}$ thermal/ohms-feet	10.63	7.49	5.02
Average values	10.60	7.47	5.01

In order for Neher-McGrath values of thermal resistances to be equal to NELA values, soil resistivity would have to be:

At 100% loss factor $\rho_e = 53$ C cm/watt
At 62.5% loss factor $\rho_e = 50$ C cm/watt
At 33% loss factor $\rho_e = 43$ C cm/watt

Other calculations on single-conductor high-voltage cables varying in conductor size from 300 to 1,150 MCM installed in outside ducts in a normal duct-bank systems it was necessary to assume a $\rho_e = 75$ C cm/watt in order to make the Neher-McGrath formulas agree with the current ratings calculated by the NELA method.

The NELA method is of course strictly empirical and the duct constants determined from an average of a large number of field surveys. It has been in use for well over 25 years; and there must of a consequence be many thousands of miles of cables operating at current ratings calculated by the use of these duct constants. So far as our experience in Canada is concerned we know of no hot-spot failures with high-voltage cables in duct-bank installations. On the contrary one is led to read with great interest the recent paper by Brookes and Starrs.[1]

Do the authors expect utility engineers operating duct-bank installations to adopt the method put forward in the paper and forthwith reduce their loads accordingly? This is a question of great importance, and we should have a categorical statement from the authors in this specific regard.

In Appendix IV the authors give a specimen calculation for a typical duct-bank installation and also a similar calculation for a pipe-type installation. In the one they use a ρ_e of 120 and in the other a ρ_e of 80. Would the authors enlighten me on the significance of these two different values for ρ_e. On this point Dr. Wiseman stated in his discussion of the paper that he was glad to learn that we can now base the duct-bank calculations on the same basis of ρ_e as pipe-type cable, but the authors have not done this in their Appendix IV.

The use of the Kennelly formula in the practical case of cables buried in the earth is at best an approximation. For the theoretical case of a heat source in a medium that is homogeneous, of uniform resistivity and temperature, the formula would apply. However, for the practical case of cables in the earth, there is considerable deviation from the ideal case such as nonuniform medium, seasonal variation of temperature gradient in the earth, nonuniform distribution of moisture in the earth, moisture migration, and other factors, which render the Kennelly formula more or less inaccurate. Thus in its use one must bear in mind these limitations.

In Europe the Kennelly formula has been used extensively, but the apparent thermal resistivity inserted in the calculations are based on that value obtained *in situ*, as measured in accordance with recommended methods. To get a very accurate value of the apparent thermal resistivity, it seems that the method to be used should exactly duplicate the cable and its operating conditions; i.e., the same diameter as the cable, the same watts loss dissipated, the same depth of burial, and at the time when the thermal conditions are most onerous. Thus in the calculation of thermal resistance from cable to ambient, it appears that the Kennelly formula can be used to a high degree of accuracy if an apparent thermal resistivity of the soil in situ is used. This measurement should automatically take into account all the factors that otherwise limit the Kennelly formula to a theoretical exercise.

There has been a great deal of investigation into the influence of moisture on soil resistivity. However, as yet there seems to be no general agreement on another basic problem, and that is the direction of the heat flow. The authors and others maintain that the heat flow is to the surface of the earth whereas other investigators claim some heat flow is downwards to a deep isothermal, about 30 to 50 feet below the earth's surface. In reference 12 Mr. Neher obtains the heat field pattern by superimposing the field based on the Kennelly formula on the temperature gradient. It is obvious from the field patterns that in the summer the heat flow is predominantly down, whereas in the winter the heat flow is to the surface. The authors give no quantitative method of evaluating the effect of the temperature gradient on the apparent soil resistivity. This could be one of the reasons for the difference between the resistivity as measured in the laboratory and in the field. An indication of the effect of change of apparent thermal resistivity is shown in a paper by de Haas, Sandiford, and Cameron,[2] wherein the effect of introducing a deep isothermal (ground water) in combination with the earth's surface as the sink has a thermal resistance of approximately 25% less than if the earth's surface was the only sink. This would indicate that the thermal resistivity of the medium is changed whereas the change in temperature distribution due to the temperature gradient should be investigated.

It should be emphasized that the Kennelly formula is applicable to steady-state conditions only. The authors realize this, of course, and attempt to compensate for this short-coming by applying a cyclical loading factor to the external thermal path. The factor they use is based upon measured values obtained on direct buried and/or pipe-type cables. Since the thermal circuit of a duct bank is quite different from that of direct buried cables, we do not agree that this same cyclical loading factor (as measured on direct buried cables) can be applied to a duct-bank installation.

Finally it is pertinent to point out that the Kennelly formula is premised upon all the heat energy flowing to the earth's surface. One must then ask the authors what they mean by ambient soil temperature. Theoretically at least the temperature of the earth at the cable depth of burial is not the ambient to be used in the Kennelly formula if the sink is the earth's surface. Why is the earth's surface temperature not the true ambient to use when applying the Kennelly formula? Is the British use of a 2/3 factor in reality a correction for the virtual sink temperature, or sink temperatures if the deep isothermal theory is valid.

REFERENCE

1. THERMAL AND MECHANICAL PROBLEM ON 138-KV PIPE CABLE IN NEW JERSEY, A. S. Brookes, T. E. Starrs. *AIEE Transactions*, vol. 76, pt. III, Oct. 1957, pp. 773–84.

2. AN ANOLOGUE SOLUTION OF CABLE HEAT FLOW PROBLEMS, E. de Haas, P. J. Sandiford, A. W. W. Cameron. *Ibid.*, vol. 74, pt. III, June 1955, pp. 315–22.

F. O. Wollaston (British Columbia Engineering Company, Ltd., Vancouver, B. C., Canada): This discussion is confined to the parts of the paper dealing with cables in ducts. The paper is in many respects most admirable, notably the coverage of skin effect in conductors of special types, proximity and eddy current effects, mutual heating effect of multicable installations, and the effect of extraneous heat sources. For the first time these are all adequately treated in one paper. The methods of calculation must, however, be critically examined before being accepted. I am disturbed to find that the methods given for rating cables in ducts lead to substantially larger conductor sizes than does the IPCEA-NELA method. By the IPCEA-NELA method I mean the method given in an Anaconda publication.[1] I believe this method is identical to that used in preparing the existing IPCEA current ratings for cables.

The Neher-McGrath method leads to much higher values for the duct heating constant (the thermal resistance from duct-bank to earth ambient) than does the IPCEA-NELA method, when the thermal resistivity of the earth is taken as 120 C cm/watt in the Neher-McGrath calculation. The value to be used for earth thermal resistivity is of paramount importance and will be discussed in more detail later. A few illustrations of the difference between the two methods will first be given.

The first application of the Neher-McGrath method which we made was to determine the conductor size for a proposed 230-kv cable installation. The calculated conductor size was 1,500 MCM, whereas by the IPCEA-NELA method the calculated size was 1,150 MCM. Some 42 miles of cable were involved in the proposed project, so the Neher-McGrath result would have meant substantial extra cost for the cable compared to the IPCEA-NELA result.

In another instance, the Neher-McGrath method was used to determine the required size of cable leads for a 75-mva transformer. The calculated size was so large as to be considered physically impractical, whereas by the IPCEA-NELA method the calculated size was practical. Rather than risk possible trouble if the IPCEA-NELA result were adopted, it was decided to use aerial bus instead of cable for these leads.

In a third case, the cable leads of a 50-mva 13.8-kv generator were to be changed

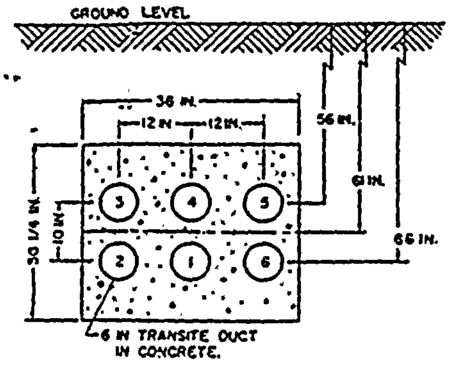

Fig. 6. Cross section of duct bank

because the associated 230-kv step-up transformer was being replaced with a 345-kv unit. The existing leads consist of two 2,500-MCM cables per phase installed in a 6-duct bank. According to the Neher-McGrath method, these cables should be approximately 3,500 MCM each if the AEIC allowable temperature of 76 C is not to be exceeded at full load in summer time. The unit has run at full load for long periods on many occasions since going into service in 1949. If our application of the Neher-McGrath method is correct, one must conclude that the existing cables have been severely overloaded many times during their service period of 8 years. No evidence of such overloading has been seen; the cables have been entirely trouble-free. There are two other units at this plant, identical in all respects to the one described above except that one of them has been in service slightly longer, the other not quite as long. No trouble has occurred on the leads of these units.

It was decided to make a temperature survey to establish the correct facts. The unit was run at full load for 5 days. Test results showed that the duct structure attained equilibrium temperature in 24 hours. The bulb of a recording thermometer was inserted 20 feet in the bottom middle duct. The details of the duct bank and cable are given in Fig. 6 and

Table XIV. Cable and Loss Data

2,500-MCM Segmental Copper Conductor, Paper Insulated-Lead-Sheathed Solid-Type, 13.8 Kv

Cable No.	Current During Test, Amperes	Watts Loss Per Foot of Cable
1	1,035	5.79
2	975	5.13
3	965	5.03
4	905	4.43
5	911	4.49
6	1,029	5.73
	Total	30.60
	Per cable average	5.1

Notes:

Ambient earth temperature during test was 19.5 C.
Cables are paired 2-3 for A-phase, 1-4 for B-phase, 5-6 for C-phase.

Diameter over conductor, inches 2.000
Cotton tape thickness, inches 0.017
Insulation thickness, inches 0.210
Diameter over insulation, inches 2.454
Copper tape thickness, inches 0.003
Sheath thickness, inches 0.125
Over-all diameter, inches 2.710
A-C resistance at 65 C = 5.41 (10^{-5}) ohms-feet

Table XIV. It was necessary to measure the air temperature in an occupied duct, since there were no empty ducts. The loading on the machine was recorded and the current division between the six cables was determined. The maximum departure from equal loading of the two cables on each phase was only 2%. After 5 days the duct air temperature was 43 C. The ambient ground temperature was 19.5 C at the same depth as the center of the duct bank. Dividing the temperature rise by 1/6 of the total losses, a thermal resistance of 4.6 ohms is obtained. Table XV shows the thermal resistances pertinent to this case as determined by the Neher-McGrath method and the IPCEA-NELA method. The experimental value (occupied duct air to earth ambient of Table XV) is in good agreement with the IPCEA-NELA value given in "duct wall to earth ambient" of Table XV, while the Neher-McGrath value is much higher. The Neher-McGrath value should be approximately equal to the IPCEA-NELA value if the two methods are to give the same results, as is obvious by inspection of Table XV. The Neher-McGrath value should be lower than our experimental value, since the former represents the thermal resistance from the outside surface of the occupied duct wall to earth ambient, while the latter represents this same resistance plus the thermal resistance from occupied duct air to the outside surface of the occupied duct wall.

One is not entitled to say that the discrepancy between the Neher-McGrath value and the IPCEA-NELA value is real unless the value of the specific thermal resistivity of the earth ρ_e is the same for both. The Neher-McGrath value in the tabulation is obtained when a value of earth thermal resistivity $\rho_e = 120$ C cm/watt and thermal resistivity of concrete $\rho_c = 85$ are used in equation 44(A) of the paper. There has never been any general agreement on what value of earth thermal resistivity is inherent in the IPCEA-NELA duct constants. Several years ago Mr. G. B. Shanklin and his coworkers in the General Electric Company investigated this extensively and concluded that the value is about 180 C cm/watt. If this conclusion is correct the discrepancy between the Neher-McGrath result and the IPCEA-NELA duct heating constant is real and serious. Our test result cited above does not give any information on this point because the earth thermal resistivity was not measured, due to lack of facilities.

If the discrepancy is real, one is led to question the soundness of the Kennelly formula used by the authors. It is based on the premise that all heat generated in the cable escapes to the surface of the earth. Some competent engineers have argued that part of the heat escapes by another path, namely to a sink deep in the earth. Mathematical development of this premise gives a result for the thermal resistance between duct bank and earth that is only about two-thirds as large as the result by the Kennelly formula. According to this, we might expect the Neher-McGrath method to agree with the NELA value if the earth thermal resistivity is taken equal to $2/3 \times 180 = 120$ C cm/watt in equation 44(A). It turns out that agreement occurs when

Table XV. Thermal Resistances Pertaining to Test

Thermal Resistance, C per Watt/Foot	Neher-McGrath	IPCEA-NELA	Experimental
Insulation	0.75	0.75	
Sheath to duct	1.52	1.82	
Duct wall	0.13		
Duct wall to earth ambient	8.75*	4.9	
Occupied duct air to earth ambient			4.01

* Calculated from equation 44(A) using $\rho_e = 120$ C cm/watt.

the earth resistivity is taken as 55 C cm/watt in equation 44(A). It does not seem likely that the value of 55 is representative of typical soil around duct banks. Many measurements in several laboratories have consistently shown that the specific thermal resistivity of earth varies from about 100 C cm/watt for a moisture content of 15%, to about 300 or 400 C cm/watt for zero moisture content. A value of 180 C cm/watt seems fairly representative of average conditions. I conclude that the validity of the Neher-McGrath method of calculating the thermal resistance from duct bank to earth ambient should be demonstrated by tests wherein the earth thermal resistivity is definitely known. Have the authors verified their findings by such tests?

Reference

1. Current Ratings for Electrical Conductors. *Anaconda Publication C-51*, McGraw-Hill Book Company, Inc., New York, N. Y., first edition, Oct. 1942.

J. H. Neher and M. H. McGrath: We are indebted to Mr. Barnes and Mr. Goldenberg for their discussions in which they summarize the present cable rating practices in Great Britain and point out some differences with American practice. From this it would appear that in most respects the practices in the two countries are similar. While the method of handling group cable ratings developed by Mr. Goldenberg may appear to differ from the method of the paper, actually both methods are derived from the same basic principles and should give identical results for the same set of conditions.

To answer their questions with regard to temperature limits and the relationship of this paper to the published rating tables, we may say that IPCEA, in collaboration with the AIEE, has under active consideration a revision of the existing current rating tables based on the methods of calculation set forth in this paper. The temperature limits will be those already adopted by IPCEA, AEIC, etc., in industry specifications.

Mr. Church has outlined a procedure for determining the effect of the loading cycle on cable ratings which will be, we fear, an enigma to most cable engineers despite the fact that it represents a challenge to those mathematically inclined. Mr. Goldenberg also has referred to a different but nevertheless mathematically involved procedure for doing this. For normal cable calculations, the tremendous amount of computations required for each individual

case is simply not warranted even if a digital computer were available to the cable engineer.

If the application of a particular load cycle to a given cable system is to be studied, we suggest that this may be done more simply, more rapidly, and more economically by using an analog computer designed for the purpose. We feel, however, that the accuracy of the method given in the paper as compared to all exact calculations which we have examined, including those of Mr. Church, is sufficient, particularly in view of the fact that any particular load cycle may never repeat itself.

The method given in the paper is an approximation, admittedly, but it has been derived from the same fundamental principles which underlie Mr. Church's method through a series of carefully considered simplifications. It should be understood that there is nothing sacred about the value of 8.3 inches used for the fictitious diameter D_x. This value happens to be the best single value to use based on the studies described in reference 3. For Mr. Church's case values of 7.1 for the 75% load factor cycle, and of 5.1 for the 60% load factor cycle are indicated. The errors in using 8.3, however, amount to only 2 and 5% high, respectively, in the conductor loss component of conductor temperature rise, which would be offset by a 10% error in the value of earth thermal resistivity employed.

Dr. Wiseman's comments in this connection are most interesting since he has often expressed the opinion that, practically, it was sufficient to consider D_x to be equal to D_e, or in other words to apply the loss factor to all of the earth portion of the thermal circuit. We can agree with this in respect to pipe-type cables, but, as he has indicated, we do not consider this further simplification desirable in the case of small directly buried cables. Neither do we consider the formula which he gives for obtaining attainment factor directly from loss factor suitable in this case. This is readily apparent from Fig. 2 of the first paper of reference 3 in our paper. Since the use of D_x has considerable theoretical justification in our opinion, we feel that it should be made a part of the general procedure for calculating the effect of the loading cycle.

The introduction of an additional thermal resistance to care for surface effects between cable and earth is an entirely different matter since this will increase the temperature rise both for steady and for cyclic loads, whereas the use of D_x is intended to give the correct result for cyclic loads on the assumption that the total thermal resistance in the circuit which is unchanged by the value of D_x is correct for steady loading. It is quite possible that such a surface effect term is present and that it may attain an appreciable magnitude in the case of small directly buried cables. We concur in the hope that this matter will be investigated further.

Mr. Thomas has noted the pioneer work of W. B. Kirke in connection with cable in duct and indicates that this work formed the basis of the present NELA-IPCEA method. Employing a duct bank configuration such as shown by Wollaston and utilizing equations 14 and 17 of the Kirke article, we find that Kirke would use a resultant thermal resistance from loaded duct wall to earth ambient of 9.0 for the worst soil in metropolitan New York and 6.00 for the best soil. These values, when compared with NELA constant of 4.9, scarcely confirm Mr. Thomas' statement to the effect that the present IPCEA-NELA method is based on or is even closely related to Kirke's work. While Kirke made some attempt to take into account the configuration of the duct-bank structure, he did not utilize resistivity as such, and as previously indicated we believe that a knowledge of this and other parameters ignored by Kirke is essential to a realistic method of handling this problem, particularly when one considers the problem of comparison between different types of systems.

As Mr. Thomas has suggested, the heat flow in a duct structure is complex, but this complexity results from the superposition of a number of heat flows any one of which, due to a particular cable, is readily determined as indicated in reference 12. We are not interested in these heat flows *per se*, but only in the resulting temperature difference between a reference cable and ambient and the corresponding thermal resistance which is fully expressed by the relatively simple equation given. True, the situation is complicated by the concrete envelope, but here extensive studies, both mathematical and on a field plotter, indicate that the equation 44(A) is sufficiently accurate in view of the inherent errors in fixing the earth resistivity and loss factor in a particular situation.

Mr. Short, at the start of his discussion, states in effect that he considers the method for determining the load capability of direct earth-buried or pipe-type cable to be "well founded" for a 100% load factor but, because of questions raised by various investigators in reference 3 of our paper, does not seem to be too sure that this is the case for other load and loss factors. All four investigators who undertook to study the problem for the Insulated Conductor Committee, however, are on record as recommending or agreeing to the method given in the present paper. In accepting the given method for buried and pipe-type cable, Mr. Short does not seem to realize that this method is based on the Kennelly formula because in the latter portion of his discussion he questions the applicability of this premise to current rating determinations for any type of underground installation, and proceeds to attempt to resurrect a number of the ghosts which plagued the Insulated Conductor Committee some 10 years ago when the latter started work on a critical review of the basic parameters involved in load capability calculations. These ghosts were subsequently laid to rest, at least to the satisfaction of the vast majority of engineers in this country. Even at that time the Kennelly formula had been in existence for over 50 years. Despite the fact that this formula is based on scientific principles found in most text books on physics and electrical engineering, some cable engineers had misgivings as to its applicability mainly because calculations by it did not appear to check with measurements in the field. This situation is discussed in reference 12 of our paper wherein it is shown that the disagreement was not due to the formula but to the fact that the field measurements had not been carried to a steady state, and that laboratory determinations of the earth resistivity were not representative of the soil *in situ*. Also, the apparent discrepancy (which appears because the direction of heat flow implied in the formula is toward the surface whereas in summer the total heat flow in the earth is obviously in the reverse direction) is explained by the application of the principle of superposition to the separate heat fields involved. As a result, cable engineers, with very few exceptions, have accepted the formula for calculations involving pipe-type and directly buried cable systems. The method of handling cables in duct, given in the paper, is a logical extension of the principles underlying the Kennelly formula in order to include in the calculations two very important variables which are not a part of the NELA-IPCEA method, namely the duct configuration and the thermal resistivity of the surrounding soil. This method is also not new. It was first described by N. P. Bailey in a paper in 1929[1] and subsequently in reference 13 of our paper.

Mr. Short also mentions the two-thirds factor, another resurrected ghost of the past. Long ago the British established that the two-thirds factor represents a difference between laboratory and *in situ* measurements of soil resistivity and that it does not stem from any lack of applicability of the Kennelly formula to the problem. Numerous British publications point out that the two-thirds factor is not to be used where the resistivity is measured *in situ* by buried sphere or by long or short cylinder. In addition, in recent years the British have developed a new laboratory sampling procedure[2] which checks not only with the buried sphere, the buried cylinder, the transient needle, but in addition also checks with results obtained on loaded cable installations.

Another ghost mentioned by Mr. Short is the deep isothermal approach (a proposal which was first suggested by Levy in 1930)[3] citing the de Haas, Sandiford, and Cameron[4] paper to give new life to this old suggestion. However, in so doing Mr. Short fails to point out that the deep isothermal in this case consists of a conducting paint electrode of an analogue model connected electrically to another electrode representing the earth's surface and hence simulating a *flowing* (not stationary) ground water sink, a somewhat unusual condition that is scarcely pertinent to the problem at hand. Incidentally, Table I of this paper gives results of an excellent analog check of the given method as applied to a duct bank.

We wish to assure Mr. Short that we have not cornered the nonferrous metal market, nor are we saying that three single-conductor cables of a given size installed in a buried pipe must have the same rating as three conductors of the same size installed in separate ducts. We should point out, however, that this has been a rule of thumb for the past 10 years or more and there are now many miles of high-voltage pipe cable in successful service which are rated and are being operated at a load capability level which Mr. Short considers incomprehensible.

Mr. Short's dilemma results solely from

the fact that he is attempting to compare the results of calculations made under a set of assumed conditions with the results of a procedure for which those same conditions are not stated and in fact are unknown. This is a situation which existed immediately following the war and is one of the ghosts previously mentioned. Conductor size determinations for cable in duct utilizing the NELA constants require no knowledge nor consideration of soil resistivity as such. On the other hand, such determinations for pipe-type cable systems by any practical method require a specific numerical assumption to be made as to the value of soil resistivity in order to arrive at an answer. By taking the stand that the concealed resistivity in the NELA constants is 120 or more, it is thus possible to obtain an advantage in favor of duct-lay cable.

Furthermore, because of the use of cable spacing factors and earth and concrete thermal resistivities in the proposed method, it will be obvious that calculations by the given method will check with those of the IPCEA method only for certain combinations of the variable parameters in the method. Since these parameters were not fixed and in fact are now unknown as regards the NELA duct heating constants, it is obviously impossible to make a factual comparison of the results obtained by the two methods. Here again, by assuming earth resistivities of 120 or 180 as both Mr. Short and Mr. Wollaston have done, the given method will result in larger conductor sizes than the IPCEA method.

Despite the fact that both Mr. Short and Mr. Thomas refer to the presumably large amount of factual data which underlie the NELA duct constants, we have been unable to ascertain the specific conditions on which these constants were based nor is there any indication that earth resistivity measurements were taken as a part of the data. About all that can be done, therefore, is to assume representative cable and duct configurations and then to calculate the earth resistivity required in the given method to match the value calculated by the IPCEA method. We cannot agree to the values given as "the average conditions on which the NELA duct constants were obtained" as stated by Mr. Short. Rather, we believe that the conditions assumed in reference 13 are much more representative, on the basis of which an average earth resistivity of 75 was obtained at 100% load factor.

We take the position, therefore, that the validity of the proposed method is not to be judged by whether or not the calculations made by it using parameters arbitrarily picked by Mr. Short (or by Mr. Wollaston) agree with calculations made by the IPCEA method. Rather we feel that the applicability of the IPCEA method to a particular case depends upon how well it checks with the method which we have proposed, and which takes into account more properly the essential parameters which are pertinent to the case at hand.

With respect to Mr. Short's specific question, we hope that utility engineers will adopt the proposed method but we do not think that they will find it necessary to reduce loads unless they have very high values of earth resistivity. Regarding the need for reduction in loads on existing circuits, it should be kept in mind that it is only relatively recently that AEIC specifications have made provision for increased permissible temperature limits for emergency periods, and for the greater portion of the period that these emergency limits have been in effect the number of companies who have utilized them is relatively small. As a result, the greater portion of the cables now in service have been selected on the basis that normal permissible copper temperature would not be exceeded under emergency conditions. Moreover, in recent years a number of *in situ* measurements have been made with the transient needle, the sphere, or the buried cylinder. Theoretical studies have shown that measurement of ultimate soil resistivity can be obtained readily with such devices. While in many cases these have been made in connection with pipe-type cable installations, they apply equally well to duct bank installations in so far as the resistivity of the soil itself is concerned. The values in general range from 50 to 100 with some higher values as the exception at certain times of the year. Moreover, over the past decade a number of pipe-type installations have been installed in this country with design resistivities in the 70 to 90 range. Under the circumstances, we do not believe that it will be found necessary in most cases to reduce the loads on existing circuits. However, we do believe that engineers will be well advised to take steps to ascertain the values of thermal resistivity which are applicable for their conditions because with the more liberal use of emergency temperature limits and the tendency for shift in many areas in the load peak from winter to summer, the existing margin may be reduced to a low level in the not too distant future.

The values of soil resistivity of 80 and 120 used in the examples of Appendix IV were chosen merely for purposes of illustration and the value of 120 rather than 80 was used in the duct lay case in order to emphasize the effect of a difference between the resistivity of earth at 120 and concrete at 85.

Unlike Mr. Short, Mr. Wollaston is very careful in his discussion to make it quite clear that his comments relating to a comparison of the results obtained by the given method and the NELA-IPCEA method is premised on his own arbitrary assumption of a concealed soil resistivity of 120 in the NELA constants and on his impression, presumably based largely on an unpublished 1947 memorandum by G. B. Shanklin, that a resistivity of 180 is representative of average conditions; consequently, the value of 55 which was obtained by back calculation from the given method utilizing his test results indicates a discrepancy in the method. We believe that if Mr. Wollaston will consult some[2-4] of the many references which have appeared in the technical literature over the past few years on determinations of soil resistivity in connection with experimental duct bank, buried cable and pipe-type cable installations, either alone or in conjunction with buried cylinders, spheres or transient needles, that he will find that there is no longer any justification for an inferred resistivity of the order of 120 in the NELA constants or for his impression that a resistivity of 180 is representative of average conditions.

In as much as no actual measurement was made of soil resistivity at the site at which Mr. Wollaston obtained an indicated value of 55, there are, of course, several possible explanations that suggest themselves. Assuming the temperature measurements were made accurately, perhaps the soil actually had a resistivity of this order of magnitude. From recent studies on soils and the effects of such matters as composition, density, compaction, particle size, etc., it is evident that it is very difficult to estimate the resistivity of a soil from appearance alone. Alternatively, it could be that the measured value of resistivity is not the ultimate value as a constant load applied for 5 days would not suffice to bring the duct structure to its ultimate temperature rise over ambient, unless, of course, it had been carrying substantially full load for some time prior to the test in question. Mr. Wollaston mentions that the temperature was measured 20 feet from the manhole but does not indicate the length of the duct run on which the test was conducted. This raises a question as to whether in his particular case there could have been any alleviation of temperature rise by longitudinal heat flow or, alternatively, by longitudinal convection effects such as were found in the tests made with ducts open and plugged.[5]

References

1. Heat Flow from Underground Electric Power Cables, Neil P. Bailey. *AIEE Transactions*, vol. 48, Jan. 1929, pp. 156–65.

2. An Evaluation of Two Rapid Methods of Assessing the Thermal Resistivity of Soil, M. W. Makowski, K. Mochlinski. *Journal*, Institution of Electrical Engineers, London, England, vol. 103, pt. A, no. 11, Oct. 1956, p. 453.

3. Cable Heating in Underground Ducts, R. D. Levy. *General Electric Review*, Schenectady, N. Y., Apr. 1930, p. 230.

4. See reference 2 of Mr. Short's discussion.

5. Temperature Rise and Current Rating of Cables Laid in Ducts, E. B. Wedmore, E. E. Hutchings. *Report, Reference F/T 103*, The British Electrical and Allied Industries Research Association, London, England, 1936.

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The Thermal Resistance Between Cables and a Surrounding Pipe or Duct Wall

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ONE step in the calculation of underground cable temperatures involves the determination of the temperature rise of the cable surface above the immediately surrounding inclosure such as a duct structure or a gas- or oil-filled pipe. Since the intervening medium is a fluid, the mode of heat transfer simultaneously involves convection, conduction, and radiation.

The semiempirical methods now in use for this determination in the case of cables in duct are not entirely satisfactory, and with the advent of gas- or oil-filled pipe-type cables there has arisen a definite need for a method of evaluation for these cable types as well.

Because of the complex nature of the problem and the number of independent variables which are present, it is impractical to cover completely all possible combinations which may be met within practice solely by tests. By developing a theoretical relationship between the variables, however, it is possible to develop procedures by which the test data available may be analyzed in such a way that relatively simple working expressions may be derived which may be applied with sufficient accuracy over the entire working range.

The theoretical relationship for the case of cables in duct was recently presented in a paper by one of the authors.[1] In the present paper this relationship has been extended to cover oil and gas pipe systems as well, and from the test data presented the requisite working expressions for thermal resistance or surface resistivity factors have been obtained.

Theoretical Considerations

The theoretical relationships given in Appendix II of reference 1 for the case of cables in duct have been expressed more completely to account for the physical characteristics of the media involved in Appendix I of this paper. The resulting equations for the the thermal conductivity between cable and duct or pipe with air or gas as the intervening medium are

$$\frac{Q}{\Delta T}(\text{gas}) = \frac{0.092\ D_s'^{3/4}\Delta T^{1/4}P^{1/2}}{1.39+D_s'/D_d} + \frac{0.0213}{\log_{10} D_d/D_s'} + 0.102 D_s'\epsilon(1+0.0167T_m)$$

watts per degree centigrade foot (1)

and with oil as the medium

$$\frac{Q}{\Delta T}(\text{oil}) = \frac{0.053 D_s'^{3/4}\Delta T^{1/4}T_m^{1/4}}{1.39+D_s'/D_d} + \frac{0.116}{\log_{10} D_d/D_s'}$$

watts per degree centigrade foot (2)

For a single cable $D_s' = D_s$, the diameter of the cable. For three cables in the pipe or duct it is customary to base D_s' on the circumscribing circle of the cables in triangular configuration, $D_s' = 2.15\ D_s$. For two cables the relationship $D_s' = 1.65\ D_s$ is satisfactory.

It will be noted that the primary variable in equation 1 is D_s'. As a result, subsequent analysis and development will be facilitated if this equation is written in the equivalent form

$$\frac{Q}{D_s'\Delta T} = \frac{0.092\Delta T^{1/4}P^{1/2}}{D_s'^{1/4}(1.39+D_s'D_d)} + \frac{0.0213}{D_s'\log D_d/D_s'} + 0.102\epsilon(1+0.0167T_m)$$

watts per degree centigrade foot inch (1A)

From the method of derivation which assumes a coaxial arrangement of the cable within the duct or pipe, the numerical constants of the first two terms of equations 1, 1(A), and 2 must be considered as being approximate only. They will serve, however, to evaluate the relative magnitudes of the terms, and the corresponding values finally employed will be based on test data.

As a practical matter, a high degree of accuracy is not required since the thermal resistivity between cable and duct or pipe represents a relatively small part of the total thermal circuit, and we are justified in materially simplifying these equations. From the standpoint of analysis of the test data and the subsequent development of working expressions, it is desirable to utilize the simple linear relationship

$$y = ax + b \tag{3}$$

where y and x are variables and a and b are constants. Equations 1 and 2 are of this form provided that the second (conduction) and third (radiation) terms may be considered as constants within the desired accuracy of the final result. Considering equation 1A the conduction term constitutes about 14 per cent of the total in the case of a typical cable in duct installation, and about 8 per cent for a typical gas-filled pipe-type installation at 200 pounds per square inch. The corresponding values for the radiation term are 63 and 43 per cent.

Normal variations in D_s'/D_d may produce considerable variation in the conduction term, but the effect on the overall picture is small, because conduction is such a small part of the total heat flow. Variations of T_m can affect the radiation term by as much as 20 per cent over a sufficiently wide operating range; however, when calculating a cable rating, with a fixed copper temperature of the order of 70 degrees to 80 degrees centigrade, the range of this variable is very small, and an accuracy of the order of 3 per cent to 5 per cent may be expected.

In the case of equation 2, the conduc-

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Table I. Test Data on Gas-Filled Pipe-Type Cable Systems

Test Number	Source	D_s'	D_d	P	Q	ΔT	T_m	$\frac{Q}{D_s'\Delta T}$	$\frac{\Delta T^{1/4}P^{1/2}}{D_s'^{1/4}}$
1	Detroit Edison Company	3.42	6.07	1	23.4	20	52	0.34	1.56
				7.8	27.3	15.6	51	0.51	4.08
				14.6	28.6	13.1	51	0.64	5.34
					28.9	17.1	50	0.49	5.71
					28.9	14.4	51	0.59	5.48
					27.5	14.0	51	0.58	5.43
2	General Electric Company	3.92	6.07	1.7	7.3	6.2	39	0.30	1.64
					11.4	9.7	45	0.30	1.63
					15.2	12.4	50	0.31	1.73
				7.8	6.8	4.7	39	0.37	2.92
					11.5	7.0	43	0.42	3.22
					14.9	8.9	45	0.43	3.42
				14.6	6.8	3.7	35	0.46	3.77
					11.2	5.8	40	0.49	4.22
					15.9	8.0	45	0.51	4.55
3	General Cable Corporation	4.90	6.07	14.6	25.9	9.2	56	0.57	4.47
4	General Electric Company	4.90	6.07	14.6	23.1	11.8	44	0.40	4.77

Table II. Test Data on Cables in Fiber and Transite Ducts Encased in Concrete

Test Number	Source	Duct	D_s'	D_d	Q	ΔT	$\frac{Q}{D_s'\Delta T}$	$\frac{\Delta T^{1/4}P^{1/2}}{D_s'^{1/4}}$
5	Barenscher	Fiber	0.69	3.5	1.0	6.4	0.226	1.74
					1.7	11.8	0.203	2.03
					2.5	15.1	0.235	2.17
					4.4	24.6	0.257	2.44
					6.6	34.2	0.281	2.65
					8.1	39.7	0.296	2.76
					12.3	56.1	0.318	3.00
			1.13	3.5	1.0	4.5	0.204	1.41
					1.7	7.1	0.207	1.59
					4.5	16.3	0.246	1.95
					8.0	30.4	0.233	2.28
					11.0	32.6	0.300	2.32
					14.6	48.5	0.268	2.82
					16.8	52.4	0.285	2.61
					18.4	58.7	0.278	2.69
			3.13	3.5	0.9	1.6	0.194	0.84
					1.7	3.2	0.173	1.00
					2.4	3.8	0.203	1.05
					4.5	7.7	0.188	1.75
					8.1	12.1	0.213	1.40
					14.8	21.9	0.217	1.63
6	Johns-Manville	Fiber	3.38	3.88	12.5	16.8	0.220	1.50
					14.9	19.2	0.230	1.56
					17.5	21.7	0.238	1.59
7	Johns-Manville	Transite	3.38	3.88	16.7	16.9	0.292	1.50
					19.6	19.4	0.299	1.55
					23.3	22.0	0.314	1.60
					26.4	24.5	0.318	1.64

tion term constitutes about 24 per cent of the total for a typical oil pipe installation. Variation is more important than is the case with the gas-pipe cable, but is still within tolerable limits.

One peculiar phenomenon has been observed. The ratio of D_d/D_s', which appears in the conduction term also, appears in the first (convection) term of equations 1 and 2 but in such a way that a change in this ratio produces an opposite, though lesser, effect on the total value of these equations. A minimum error should, therefore, prevail when the conduction term is treated as a constant if the denominator of the convection term also is treated as a constant. This procedure will simplify the convection term but it will have the effect of approximately halving its numerical constant as compared with equations 1 and 2 since the numerical value of the denominator omitted is in the order of two. Actually the test data was analyzed both with and without this simplification, and no apparent change in consistency in the results was observed.

Analysis of Test Data

It follows from the preceding discussion that the test data for cables in duct and for gas-filled pipe-type installations may be analyzed by plotting the observed values of

$$y=\frac{Q}{D_s'\Delta T}; \quad \text{against } x=\frac{\Delta T^{1/4}P^{1/2}}{D_s'^{1/4}} \tag{4}$$

The data given in Table I were compiled from tests on gas-filled pipe-type cable systems by The Detroit Edison Company,[3] the General Electric Company, and the General Cable Corporation. These data are plotted in Figure 1 and the values of a and b in equation 3 are established as $a=0.070$; $b=0.20$.

Table II presents similar data for cables in single dry fiber and Transite ducts in concrete taken from the Barenscher[4] and Johns Manville tests discussed in reference 1. These data also are plotted in Figure 1 where it will be seen that the Transite duct points fall on the gas in pipe curve, but the fiber duct points result in a different curve having the same value of $a=0.07$ but $b=0.10$. This difference may be explained by the fact that the duct wall departs from an isothermal as a result of the relatively high thermal resistance of the materials used, that of the dry fiber being considerably higher than that of the transite.[1]

The test data for oil-filled pipe-type cable systems from tests by The Detroit Edison Company,[3] the General Electric Company, and the Okonite Company are presented in Table III and plotted in Figure 2. In this case, the analysis has been made by plotting the observed values of

$$y=\frac{Q}{\Delta T}; \quad \text{against } x=D_s'^{3/4}\Delta T^{1/4}T_m^{1/4} \tag{5}$$

and results in the values of $a=0.025$ $b=0.60$ in equation 3.

It will be seen from the analysis of the test data that the agreement between theoretical and observed numerical constants of the simplified convection term is extremely good in the case of oil as the medium, but in the case of gas, the observed value of 0.07 is somewhat higher than the expected value of about 0.046. This is rather surprising since tests number 2 (with gas) and number 9 (with oil) which are consistently close to the established curves in Figures 1 and 2 were made with the same physical setup which remained unchanged throughout the tests except for the change in the media employed. Therefore, we should expect the ratio of values obtained to be the same as the ratio of the numerical constants of the convection terms in equations 1 and 2.

This discrepancy seems to be due to the fact that in the case of several cables within the pipe, a condition of the majority of test data, there is an additional circulation of the gas between the cables themselves which is not properly accounted for by the use of an equivalent diameter for the three cables, but which is apparently not effective when a more viscous medium such as oil is employed.

As indicated before, however, a high degree of accuracy is not required, and it is

[illegible]

Table III. Test Data on Oil-Filled Pipe-Type Cable Systems

Test Number	Source	D_s'	D_d	Q	ΔT	T_m	$\frac{Q}{\Delta T}$	$D_s^{3/4}\Delta T^{1/4}T_m^{1/4}$
8	Detroit	4.83	6.07	26.2	8.9	49	2.94	104
9	General Electric Company	3.92	6.07	6.6	3.0	37	2.19	55
				11.4	4.5	44	2.55	69
				16.5	5.8	48	2.88	79
10	Okonite Company	4.50	6.13	4.1	2.5	25	1.65	43
				9.4	4.4	31	2.14	68
				9.4	5.4	23	1.75	63.5
				1.1	7.5	38	2.81	79
				21.6	8.8	41	2.45	85.5
				35.2	11.4	50	3.09	106
				34.9	11.7	48	2.98	132

felt that a working expression based on the foregoing analysis will be sufficiently accurate.

Working Expressions

In formulating the thermal resistance between cable and duct, it is customary to express this resistance in terms of an equivalent surface resistivity factor, assuming that the entire resistance was concentrated at the cable surface, according to the expression

$$H_{sd}=0.00411\,\frac{\beta}{D_s'}\text{ thermal ohm feet} \qquad (6)$$

in which β is expressed in degrees centigrade square centimeters per watt. Since $H_{sd}=\Delta T/Q$ it follows from equation 6 that

$$\beta=243\,\frac{D_s'\Delta T}{Q}\text{ degree centigrade centimeter per watt} \qquad (7)$$

and

$$\Delta T^{1/4}=0.253\frac{\beta^{1/4}Q^{1/4}}{D_s'^{1/4}}\text{ (degrees centigrade)}^{1/4} \qquad (8)$$

It is thus possible to develop working expressions in terms of β in the case of cables in duct- or gas-filled pipe by substituting equations 7 and 8 in equations 3 and 4 with the appropriate values of a and b. In the case of oil-filled pipe a simpler expression is obtained in terms of H_{sd}.

For cables in single dry fiber ducts

$$\beta=\frac{13{,}700}{\beta^{1/4}\left(\dfrac{Q^{1/3}P}{D_s'}\right)^{1/2}+5.7}\text{ degrees centigrade square centimeters per watt} \qquad (9)$$

For cables in other types of single dry ducts and in gas-filled pipe

$$\beta=\frac{13{,}700}{\beta^{1/4}\left(\dfrac{Q^{1/3}P}{D_s'}\right)^{1/2}+11.3}\text{ degrees centigrade square centimeters per watt} \qquad (10)$$

For cables in oil-filled pipe

$$H_{sd}=\frac{40}{H_{sd}^{1/4}(QD_s'^{3}T_m^{3})^{1/4}+24}\text{ thermal ohm feet} \qquad (11)$$

The value of β from equations 9 and 10 is plotted in Figure 3 as a function of $(Q^{1/3}P/D_s')^{1/2}$ and the value of H_{sd} from equation 11 appears in Figure 4 as a function on $(QD_s'^{3}T_m^{3})^{1/4}$. Also indicated on these figures are the values of these parameters for typical conditions.

In the case of cable in fiber duct, the thermal resistance of the duct wall is appreciable and should be accounted for. This is most readily accomplished by modifying equation 6 to include this resistance. Thus

$$H_{sd}'(\text{fiber})=0.00411\frac{\beta}{D_s'}+0.33\text{ thermal ohm feet} \qquad (12)$$

in which the second term represents the difference in thermal resistance between a 4-inch fiber duct and the corresponding section of concrete which it replaces.

Discussion of Values for Cables in Duct

It will be seen that the method of determining the thermal resistance between cable and duct presented herein differs somewhat from the method given in reference 1, although the results are substantially the same for terra cotta and fibre ducts. For Transite ducts, the values of thermal resistance derived in a more fundamental manner in the present paper, are slightly lower than those appearing in the reference, being equal to those assumed for terra cotta.

It will be recalled that the reasoning used in developing algebraic expressions for these values assumes an isothermal duct wall. The test data presented in

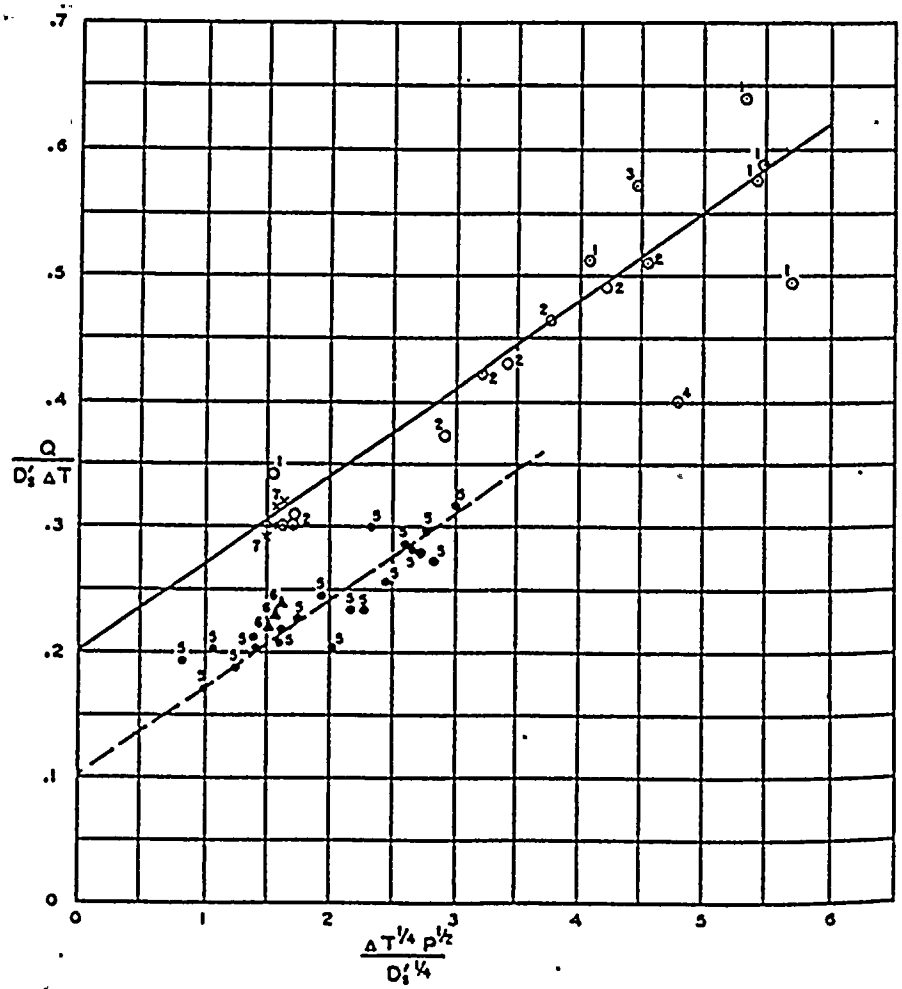


Figure 1. Analysis of test data for cables in duct- and gas-filled pipes

Table II and plotted in Figure 1, however, indicate a good correlation even where there is substantial deviation from the assumed isothermal as indicated by the basic data on which the table is based. Within the range covered by the data, including the departure from the isothermal changes the resulting constants somewhat but does not invalidate the method of analysis.

It follows therefore that a considerable variation in β for cables in single-fibre ducts may be expected depending upon the relative thermal resistivities of the duct wall and the surrounding medium, and other data which has come to the authors' attention confirms this. Thus the curve of Figure 3 for fibre duct should be considered as an upper limit.

Similarly, the application of the values given for single ducts to the case of cables in a multiduct structure, depends upon the effect which the total heat field has in further changing the temperature gradients around the individual duct walls. The data given by Smith in his discussion of reference 1 indicates a value of β for multiple-fiber ducts in concrete corresponding closely to the curve for cable in pipe.

As indicated in reference 1, additional test data taken on multiple-duct assemblies are desirable to definitely establish the limits under these conditions.

For reasons also indicated in reference 1 these values are not directly comparable to the values adopted by the Insulated Power Cable Engineers Association[5] and are not directly adaptable to their calculation procedure.

Conclusions

1. The theoretical relationships between the various quantities involved in the effective thermal resistance between cables and a surrounding single duct or pipe have been developed in a manner which properly accounts for the simultaneous modes of heat transfer by convection, conduction, and radiation.

2. By means of these relationships certain test data on cables in duct and in gas- and oil-filled pipes have been analyzed and working curves are presented for determining the thermal resistance for any particular case which may be encountered in practice.

3. Under typical conditions representative values of the equivalent surface resistivity factor β for use in equation 6 are 800 degree centigrade square centimeters per watt for cables in pipe, single dry terra cotta or transite ducts at atmospheric pressure, 450 for cables in gas-filled pipe-type installations at 200 pounds per square inch, and 350 for cables in oil-filled pipe-type installations. Representative values of β for cables in single dry fiber ducts will vary from 850 to 1100.

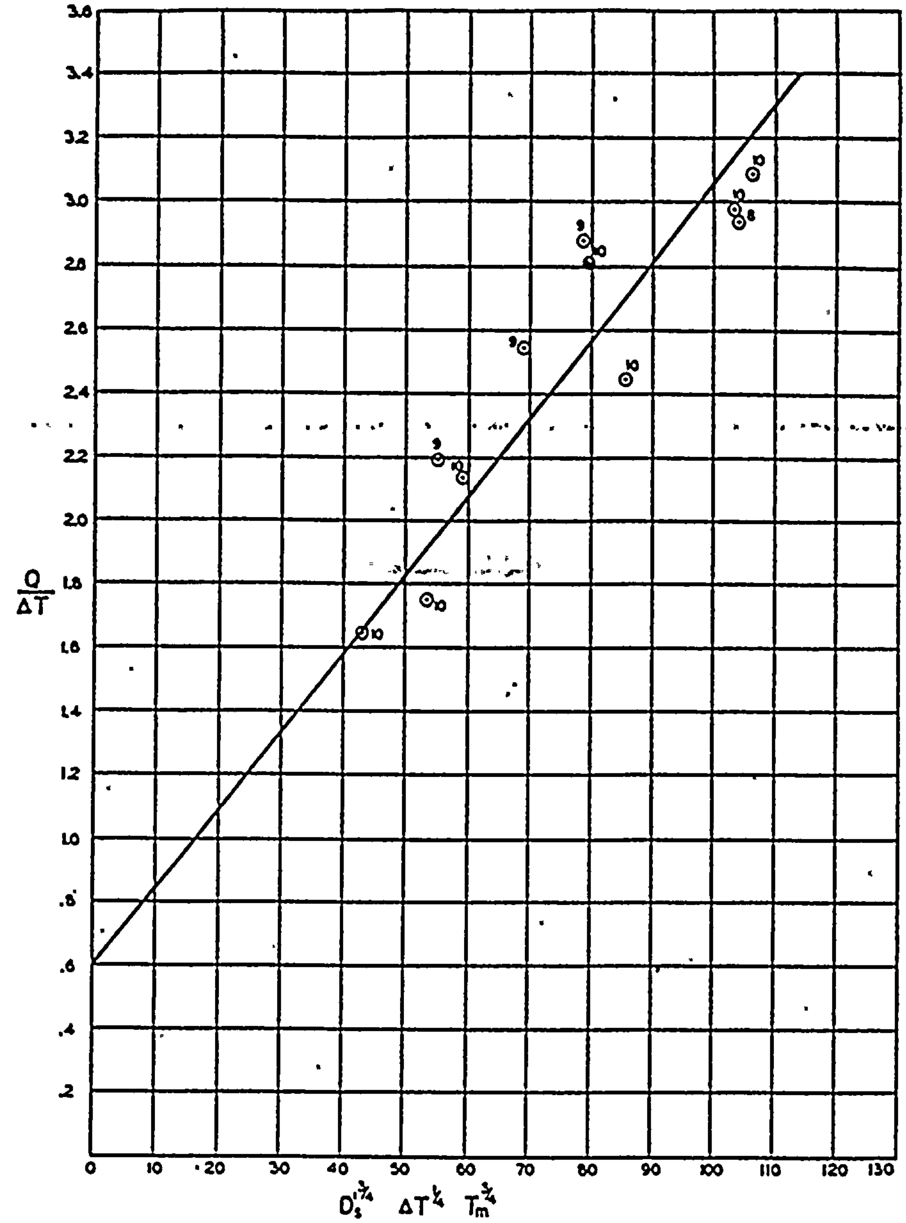


Figure 2. Analysis of test data for cables in oil-filled pipe

Appendix I. Theoretical Development of Thermal Conductivity between Concentric Isothermal Cyclinders with Gas or Oil as the Intervening Medium

The mechanism of heat transfer between a cylindrical radiator and an enveloping isothermal enclosure through an intervening fluid medium is such that a portion of the total heat flow Q is carried by convection Q_{cv}, a portion by conduction Q_{cd}, and the remainder by radiation Q_r. In formulating the components of the thermal circuit, therefore, it is more convenient to work in terms of thermal conductances rather than thermal resistances since the former quantities are directly additive. Thus, if ΔT is the temperature drop in degrees centigrade across the circuit

$$\frac{Q}{\Delta T}=\frac{Q_{cv}}{\Delta T}+\frac{Q_{cd}}{\Delta T}+\frac{Q_r}{\Delta T} \text{ watts per degree centigrade foot} \quad (13)$$

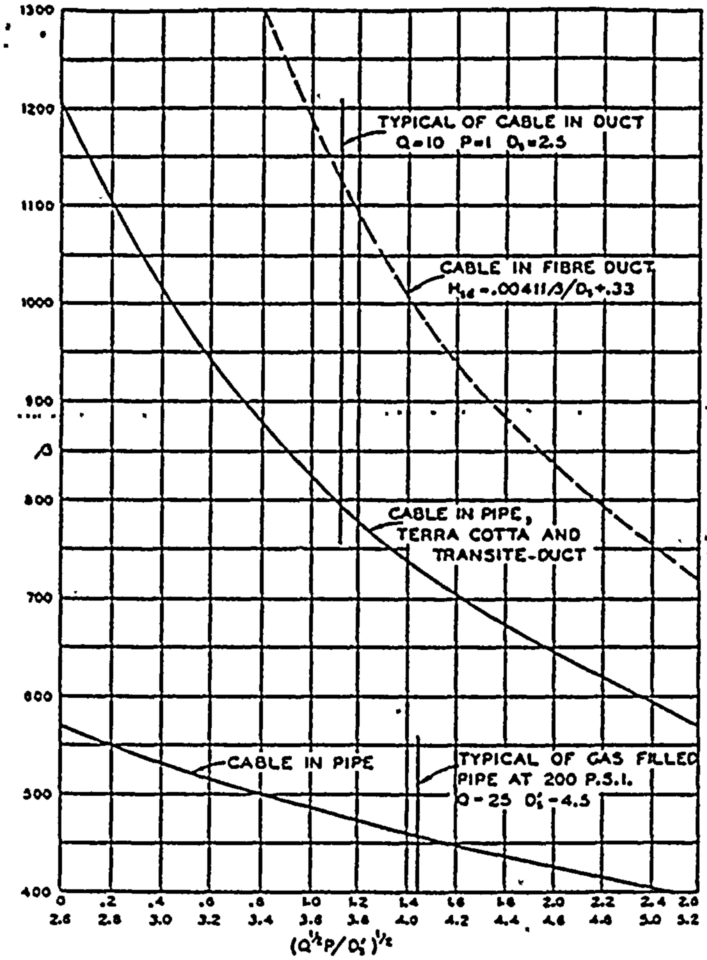
The phenomenon of convection involves the conception of the temperature drop being concentrated in two films, one at the surface of the cylindrical radiator of diameter substantially equal to the diameter of the radiator D_s in inches, and one at the surface of the enclosing isothermal surface which will be considered also being cylindrical of diameter D_d. The following formula based on McAdams[2] (equation 42, page 251, 1st edition only) is applicable to either film.

$$Q_{cv}=122D_f^{3/4}\Delta T_f^{5/4}K \text{ watts per foot} \quad (14)$$

in which D_f is in inches, and

$$K=\left(\frac{\delta^2 C_p g c}{\mu \ \rho^2}\right)^{1/4} \text{ watts per centimeter}^{7/4} \text{ degrees centigrade}^{5/4} \quad (15)$$

The significance of the components of equation 15 and representative values for gas (air or nitrogen) and Suniso number 6 oil are given in Table IV.



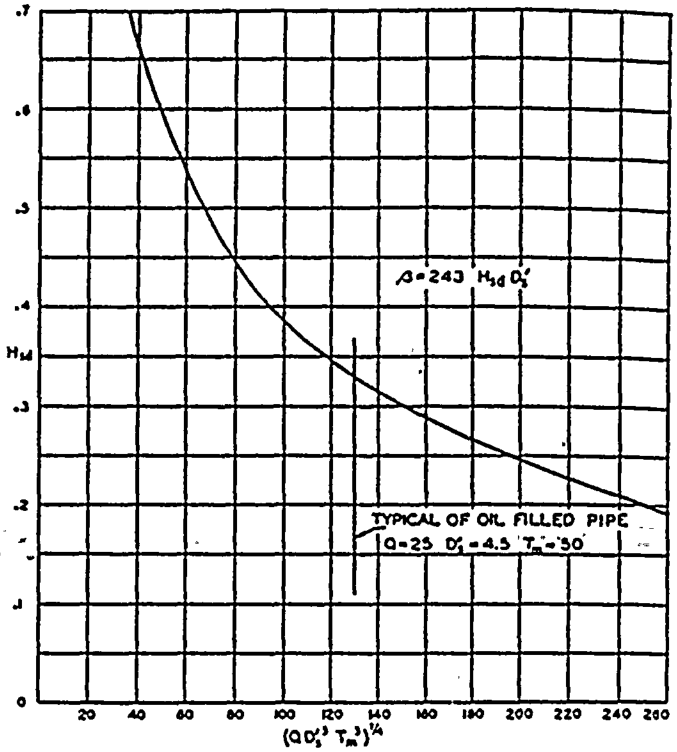


Figure 3 (left). Values of β for cables in dry single ducts and gas-filled pipe

Figure 4 (above). Values of H_{sd} for cables in oil-filled pipe

In the case of air or inert gas, these physical properties are substantially independent of temperature over the working range but the density is a direct function of the pressure. Thus, if P represents the pressure in atmospheres, from equation 15

$$K_g = 0.000755P^{1/4} \text{ watts per centimeter }^{1/4} \text{ degrees centigrade }^{1/4} \qquad (16)$$

When oil is employed as the medium the physical constants are substantially independent of pressure and temperatures with the exception of the viscosity which for the type of oil commonly employed (Suniso number 6) may be taken as varying inversely as the cube of the temperature according to the relationship

$$\mu_o = \frac{94{,}000}{T_m^3} \text{ grams per centimeter second} \qquad (17)$$

The value of K for oil thus becomes

$$K_o = 0.000434T_m^{1/4} \text{ watts per centimeter}^{1/4} \text{ degrees centigrade }^{1/4} \qquad (18)$$

The solution of equation 14 for the two films in series and with equation 16 or 18 substituted therein is given with sufficient accuracy by the expressions convection

$$\frac{Q_{cv}}{\Delta T}(\text{gas}) = 0.092\frac{D_s^{3/4}\Delta T^{1/4}P^{1/2}}{1.39+D_s/D_d} \text{ watts per degree centigrade foot} \qquad (19)$$

$$\frac{Q_{cv}}{\Delta T}(\text{oil}) = 0.053\frac{D_s^{3/4}\Delta T^{1/4}T_m^{1/4}}{1.39+D_s/D_d} \text{ watts per degree centigrade foot} \qquad (20)$$

From a theoretical standpoint the expression for the conduction component should take into account any eccentricity between the cylindrical radiator and the enveloping isothermal enclosure. In the practical case of cables in duct or pipe the cables will not rest uniformly on the bottom of the duct, and also in the case of a nonmetallic duct the duct wall is not strictly maintained as an isothermal. Since these effects cannot be evaluated, the familiar expression for the resistance between two concentric cylinders in terms of the dimensions of the cylinders and the thermal resistivity of the medium will be used. Thus

conduction

$$\frac{Q_{cd}}{\Delta T}(\text{gas}) = \frac{0.0213}{\log_{10} D_d/D_s} \text{ watts per degree centigrade foot} \qquad (21)$$

$$\frac{Q_{cd}}{\Delta T}(\text{oil}) = \frac{0.116}{\log_{10} D_d/D_s} \text{ watts per degree centigrade foot} \qquad (22)$$

The radiation component with gas as the medium is given with sufficient accuracy by the following expression based on McAdams[3] equation 5, page 61, first edition.

Radiation

$$\frac{Q_r}{\Delta T}(\text{gas}) = 0.102D_s\epsilon(1+0.0167T_m) \text{ watts per degree centigrade foot} \qquad (23)$$

in which ϵ is the emissivity coefficient of the surface of the cable and T_m is the average temperature of the medium. The radiation term is ineffective when oil is the medium.

The over-all thermal conductivity is obtained by substituting equations 19, 21, and 23 or equations 20 and 22 in equation 13.

Table IV

Symbol	Quantity	Units	Gas at 50 C	Oil at 50 C
ρ	Thermal resistivity	C cm/watt	3,900	715
μ	Average absolute viscosity	grams/cm sec.	0.000195	0.75
δ	Density	grams/cm^3	0.00110 P	0.906
C_p	Specific heat at constant pressure	watt sec/C gram	0.995	2.10
g	Acceleration due to gravity	cm/sec^2	980	980
ϵ	Thermal coefficient of expansion	1/C	0 00310	0.00068

Appendix II. List of Symbols

Q = total heat flow from equivalent sheath to duct wall or pipe in watts per foot

ΔT = temperature drop in degrees centigrade

P = pressure in atmospheres

D_s = diameter of the sheath in inches

D_s' = equivalent diameter of a group of cables in inches

D_d = inside diameter of the duct wall or pipe in inches

T_m' = average temperature of the medium in degrees centigrade

ϵ = coefficient of emissivity of the cable surface

x and y = rectangular coordinates

a and b = experimentally determined constants

H_{sd} = thermal resistance between equivalent sheath and duct wall or pipe in thermal ohm feet

H_{sd}' = equivalent thermal resistance between equivalent sheath and fibre duct wall including the increased thermal resistivity of the duct wall over that of the surrounding medium in thermal ohm feet

β = equivalent surface resistivity factor in degrees centigrade square centimeters per watt

ρ = thermal resistivity in degrees centigrade centimeters per watt

μ = average absolute viscosity in grams per centimeters second

δ = density in grams per cubic centimeter

C_p = specific heat at constant pressure in watt seconds per degree centigrade gram

g = acceleration due to gravity in centimeters per second squared

c = thermal coefficient of expansion in centimeters per centimeter degree centigrade

K = a factor dependent upon the physical constants of the medium in watts per centimeter$^{7/4}$ degrees centigrade$^{1/4}$.

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1. The Temperature Rise of Cables in a Duct Bank, J. H. Neher. *AIEE Transactions*, volume 68, part I, 1949, pages 540-49.

2. Heat Transmission (book) W. H. McAdams. McGraw-Hill Book Company, New York, N. Y., first edition, 1933.

3. Thermal Characteristics of a 120-Kv High-Pressure Gas-Filled Cable Installation, W. D. Sanderson, J. Stiicher, M. H. McGrath. *AIEE Transactions*, volume 67, Part I, 1948, pages 487-98.

4. A Study of the Temperature Distribution in Electric Cables in Underground Ducts, P. J. Barenscher. *Thesis*, Department of Electrical Engineering, University of Wisconsin (Madison, Wis.), 1925.

5. Current Carrying Capacity of Impregnated Paper, Rubber and Varnished Cambric Insulated Cables. *Publication Number P-29-226*, Insulated Power Cable Engineers Association (New York, N. Y.), first edition, 1943.

Discussion

R. H. Norris and Mrs. B. O. Buckland (General Electric Company, Schenectady, N. Y.): Efficient work in the heat-transfer field on a variety of applications requires awareness of the definitions and units, in order to avoid confusion and misunderstanding. In this paper and other papers written by cable engineers, confusion arises as to the exact meaning of the expression "thermal resistivity." Resistivity as normally defined (by the American Standards Association (ASA) for example) is a property of a substance and is not affected by its geometry; for example, the resistivity of copper has a constant value at any specified temperature, while its resistance depends on its size and shape. Then the use of the word "resistivity" for surface phenomena is a misuse of the term.

To show how the distinction between resistance and resistivity enters into the picture, the thermal circuit for a single-conductor cable in air is given in Figure 1 of the discussion.

In this figure, t_{cu}, t_{sh}, and t_a are temperatures of copper, sheath, and ambient, respectively, δ is insulation thickness, ρ is thermal resistivity of the insulating material, A_L is the log mean area of the insulation for heat flow, A_{sh} is sheath area, and β_c and β_r are the cable engineers' terms for "surface resistivity" for free convection and radiation. Each fraction in the Figure is the thermal resistance; and when resistances and temperatures are known, the heat dissipation of the cable is known. But in order for the resistances to be dimensionally consistent, the dimensions of ρ must be different from the dimensions of β, and therefore ρ and β should not be called by the same name.

Since the definition of ρ as thermal resistivity conforms to ASA standards, it might be better to denote β as thermal resistance of a unit surface. Its reciprocal h, is defined as surface heat transfer coefficient, or alternatively as surface film conductance. The concept of conductance is particularly applicable here, as the total film conductance is the sum of h_r and h_c, and therefore numerically easier to handle.

The units of length used in the paper seem to be a mixture of metric and engineering units. A combination of square centimeters with feet has no logical basis. If any cable dimensions were expressed in centimeters, the mixture would be logical although not standard; but since dimensions are not so expressed, it seems time to abandon this practice and use the engineering system of units throughout.

It is therefore proposed that the AIEE Committee on Insulated Conductors take steps to persuade its adherents to become familiar with ASA standards and to use them where they apply.

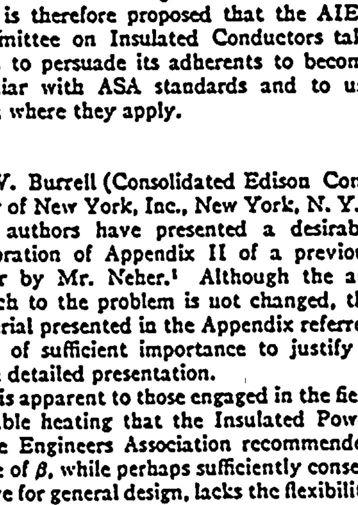


Figure 1. Thermal circuit for single conductor in air

R. W. Burrell (Consolidated Edison Company of New York, Inc., New York, N. Y.): The authors have presented a desirable elaboration of Appendix II of a previous paper by Mr. Neher.[1] Although the approach to the problem is not changed, the material presented in the Appendix referred to is of sufficient importance to justify a more detailed presentation.

It is apparent to those engaged in the field of cable heating that the Insulated Power Cable Engineers Association recommended value of β, while perhaps sufficiently conservative for general design, lacks the flexibility needed in comparing alternative constructions. Precise determinations of β for various types of installations may not be possible because of inherent variations in the physical constants involved; however, as additional test data are compiled, the probable range of β, for a particular case, will be better understood, thereby making possible more realistic comparisons. The authors clarify our conception of the effect of the various parameters involved in the temperature drop between cable surface and duct or pipe wall. For a given system of cables in duct or pipe, the thermal resistance will decrease sensibly with increasing watts loss.

W. B. Kirke[2] introduced this modification which is taken into account in determining cable ratings for the Consolidated Edison system.

As one follows the assumptions made in this paper, there appear various points to which exception might be taken on the ground that they are not substantiated, for example: the assumption of the same constant in the expression for the convection film at the cable surface and at the inner duct wall, the treatment of conduction on the basis of a concentric system, and the arbitrary assumption of an emissivity coefficient of the cable surface of 1.0. Yet, the important point is that putting all of these various assumptions together in the particular form given in the paper, the overall end result does produce expressions which are reasonably satisfactory.

It is unfortunate that, while the basic equations and the selection of parameters have a reasonably sound theoretical basis, the final working expressions given are essentially empirical and do not allow an accurate determination of the separate effect of the three modes of heat transfer. On the average, the calculated values of $Q/\Delta T$ for the oil-filled pipes, gas-filled pipes, and cable in duct are about 5 per cent, 15 per cent, and 55 per cent higher, respectively, than the measured values given in Tables I, II, and III of the paper. Specialists in the field of cable heating would be interested in knowing which component or components are responsible for these discrepancies so that extrapolation into new fields could be made with confidence.

It is stated in the paper that the agreement between theoretical and empirical numerical constants of the simplified convection term is close for the case of an oil medium, but is off appreciably for the case of a gas medium. It also can be said that the conduction-radiation constant agrees with theory for the case of a gas medium; however, for the case of an oil medium, the constant theoretically appears to range from 0.60, as given in the paper, to nearly twice that value, depending upon the values of D_s' and D_d involved.

From the over-all standpoint, it nevertheless appears that the expressions for β and H_{sd}, as given in equations 9, 10, and 11 of the paper are quite workable and agree with test data as well as could reasonably be expected. A high degree of accuracy in the calculation of allowable current ratings of cables is not yet to be expected but important work has been done in the past few years in clarifying our understanding of heat flow through duct structures and the earth, and this paper is an important contribution to such understanding.

References

1. See reference 1 of the paper.

2. The Calculation of Cable Temperatures in Subway Ducts, W. B. Kirke. *AIEE Journal*, volume 49, 1930, page 555.

R. J. Wiseman (The Okonite Company, Passaic, N. J.): I like the author's paper very much. It explains the three methods of heat flow from a cable to a surrounding medium, namely, conduction, convection, and radiation. Also, they give the various parameters which influence each factor namely, cable diameter, temperature, and temperature difference, and viscosity of the medium. The various formulas look quite formidable when we note terms raised to fractional powers. It is not easy to obtain the constants for each formula as they are dependent on conditions not easily calculable so it is necessary to get test data and work back to numerics which will give the desired results. It so happens that as all three modes of heat transfer are functioning at the same time, a change in dimensioning tends to work in opposite directions, reducing thereby the effect of diameter. Also the range in temperature is not great and as we take the one-fourth power of temperature difference and three-fourths power of temperature, the variation with temperature is not great.

About two years ago we decided to restudy the thermal constants we obtained when we originally set up the Oilostatic cable system. At that time we used the cylindrical log formula of ratio of internal pipe diameter to circumscribed circle over the assembled conductors, and also a constant which was a function of the temperature.

Our more recent tests showed that the thermal resistance was almost independent of temperature (a variation of about 10 per cent between 30 and 61 degrees centigrade) for an oil pressure zone and a very few per cent for a gas pressure zone at 200 pounds per square inch. We also noted that within the accuracy of testing we could safely assume the thermal resistance to vary as inversely as the diameter of the shielding tape over the insulation. As a result, we have set up two simple formulas for the determination of the thermal resistance of the pressure zone for three cables in a pipe, namely, for oil-pressure system $H=1.60/D$ thermal ohms per foot per conductor where, D is the diameter in inches over the shielding tape; and $H=2.58/D$ thermal ohms per foot per conductor for a gas pressure zone operating at 200 pounds per square inch. You will find these values of thermal resistance for the pressure zones amply accurate.

As the authors refer to the surface resistivity factor β, the values of β comparable to the above constants in $H=0.00411\ \beta/D$ are $\beta=390$ for an oil-pressure system as compared to 350 given by the authors and $\beta=627$ for a gas-pressure system at 200 pounds per square inch as compared to 450 given by the authors. We are quite confident in our values and have been using them for over a year.

Paul Greebler (Johns-Manville Corporation, Manville, N. J.): In this paper the authors have contributed immensely toward an understanding of the mechanisms of heat transfer from the cable to its surrounding pipe or duct wall. The theoretical analysis was necessarily based upon the simplifying assumption of a coaxial cable in duct arrangement. This does not, however, detract from the value of the analysis given in the paper, since this analysis gives the order of magnitude contributed by each of the three mechanisms of heat transfer.

The authors have assumed for cable in duct that the component of the thermal conductivity due to radiation can be treated as a constant in the range of normal operating temperatures. Only the component due to convection was considered as variable with changing cable diameter and heat flow. This assumption does not lead to a true picture of the variation in thermal resistivity with heat flow, or more fundamentally, with cable temperature. Mr. Barnett and I have stated in our paper[1] that the decrease in thermal resistivity with increasing sheath temperature is caused primarily by variation in the radiation component of heat transfer, and that the effect of temperature variations on convection are negligible over the normal operating range. This statement is verified by calculations based upon equation 1A of the Buller-Neher paper, which is repeated here:

$$\left(\frac{Q}{D_s'\Delta T}\right)=\frac{0.092\,\Delta T^{1/4}p^{1/2}}{D_s'^{1/4}(1.39+D_s'/Dd)}+ \qquad (1A)$$

(convection)

$$\frac{0.0213}{D_s'\log D_d/D_s'}+0.102\epsilon(1+0.0167T_m)$$

(conduction) (radiation)

in watts per degree centigrade foot inch. The emissivity factor, ϵ, is assumed to be unity at atmospheric pressure.

Table I of the discussion lists two representative sheath temperatures from our test data on fiber duct in concrete, and these temperatures might very well be representative of the operating range of a cable. The term $(Q/D_s'\Delta T)$ evaluated in equation 1A is inversely proportional to the surface resistivity factor, β.

The three terms in the equation give the thermal conductivity components due to convection, conduction, and radiation respectively. As we increase the sheath temperature over the range shown, the increase in the radiation term produced by substituting our experimental data in the Buller-Neher equation is five times greater than that of the convection term. This shows that the experimentally observed decrease in β over this range is due almost entirely to the increase in the radiation term. These calculations are based, of course, on the rather large cable size that we employed in our tests. A smaller cable size will increase the effect of the convection term only slightly, however, and not nearly enough to make its variation with temperature equal to that of the radiation term. Identical calculations with our data on Transite in concrete, Transite in air, and fiber in air, show similar relative variations in the radiation and convection terms.

The authors have neglected the variation in radiation component of conductivity with temperature, pointing out that these variations are quite small. This is justifiable from a practical standpoint. However, the variations in the convection component with temperature also should be neglected for practical considerations, since, as is shown in Table I of the discussion this factor is even smaller than the change in the radiation term. This would considerably simplify the Buller-Neher equations for the surface resistivity factor. In their equations 9 and 10, the surface resistivity factor, β, depends upon the fourth root of the heat flow. This does not have much significance since it is based upon the variation in the convection term, a second order effect compared with the radiation term. Similarly the dependence of β upon the square root of the sheath diameter is doubtful, since the change from a fourth root to a square root dependence in the convection term also was based on the very small change in convection conductivity with temperature.

The foregoing discussion was confined to cable in duct with air as the intervening fluid. Its applicability to cable in gas-filled pipe at high pressures, where convection becomes the principal mechanism of heat transfer, requires further study.

The authors have done an excellent job in helping to establish the theoretical groundwork necessary to both encourage and guide experimental workers in the duct heating problem.

Reference

1. Heat Transfer Study on Power Cable Ducts and Duct Assemblies, Paul Greebler, Guy F. Barnett. *AIEE Transactions*, volume 69, part I, 1950, pages 357-67.

A. H. Kidder (Philadelphia Electric Company, Philadelphia, Pa.): This paper by Buller and Neher, together with two previous papers by Mr. Neher,[1,2] completes presentation of the steady-state considerations involved in a project which was started about four years ago when Philadelphia Electric Company interested Mr. Neher in undertaking an investigation of fundamental relationships, as necessary to determine approximately what pipe-type cable circuit load ratings would be accurately comparable with the load ratings of conventional cable circuits in ducts.

The thermal resistance through the spaces between the cable sheaths and the pipe or duct wall inclosures is an important link in the thermal circuit. It had been hoped that a general relationship could be developed in such a form that all of the differences be-

Table I. Greebler-Barnett Data

Lead Sheath Temperature	Inside Duct Wall Surface Temperature*	Mean Temperature T_m	Temperature Drop ΔT	Buller-Neher Equation 1A: Convection Term	Buller-Neher Equation 1A: Radiation Term	Greebler-Barnett Data β in °C(cm)²/w
66.2	46.8	56.5	19.4	0 062	0.198	990
77.2	53.6	65.4	23.6	0 065	0.213	930
			increase —	0 003	0.015	60 — decrease

*Temperatures are in degrees centigrade. The inside duct wall surface temperature is an average value.

[illegible]

tween cables in air in ducts and cables in high-pressure gas or oil-filled pipes could be explained in terms of the physical constants which characterize the respective fluids and the pertinent geometrical relationships.

The method presented by Buller and Neher has approximately achieved this result, at least to the extent of permitting the correlation of data obtained by various investigators at various times in various constructions. It does not disturb me particularly to find that there is some apparent difference between the effects of Transite and fiber duct walls, respectively, under the conditions which prevailed at the time the tests were made. I think we should hesitate to attach much significance to these apparent differences because there was no attempt to control the moisture content in the fiber or the Transite, or even to make the tests under conditions comparable to those to be expected in the usual exposures to natural but variable moisture conditions to be encountered in underground structures. The significant point is that Buller and Neher have obtained a correlation which now permits estimating the thermal resistance from cable to pipe or duct wall with sufficient accuracy, so that little, if any, practical improvement in cable load ratings can be gained by introducing further refinements in their analysis of this part of the thermal circuit.

REFERENCES

1. THE TEMPERATURE RISE OF BURIED CABLES AND PIPES, J. H. Neher. *AIEE Transactions*, volume 68, part I, 1949, pages 9–17.

2. See reference 1 of the paper.

F. H. Buller and J. H. Neher: Mr. Norris and Mrs. Buckland have taken us somewhat to task for our apparent inconsistency in expressing our physical units in one system and our geometric units in another. For better or worse it has long been the custom in cable rating procedure to express the physical units involved in the watt-second-centimeter-gram system, and to express lengths in feet and diameters in inches. In developing our equations it would have been more consistent to have expressed the latter quantities also in centimeters, and then to have converted the final expressions to the system of measurement used in practice. We chose to use the mixed system throughout, however, in order that the reader might be able to use any equation in the development, directly, without encountering the uncertainty which inevitably arises as to whether you multiply or divide by the transformation constants.

The use of the term "surface resistivity factor" is a slightly different matter, and as our mentors have pointed out, it has dimensions which are not those of true, or volumetric, "resistivity." Here again, this nomenclature has been hallowed by time and is thoroughly understood by cable engineers, for whom this paper was written. It should be stressed, however, that this "surface resistivity" is not a fundamental physical quantity, in the sense that volumetric resistivity is; but as pointed out, is the resistance of a unit surface of a film which, purely for purposes of convenience, is assumed arbitrarily to represent the entire thermal resistance of the composite heat transfer effects operating in the region between cable sheath and duct wall. It is unfortunate that we do not have a more distinctive name for it.

Mr. Burrell has presented a thoughtful discussion of the assumptions which we have made in developing the theory used for correlating the test data. In this respect, a book by Prof. McAdams[1] gives a constant for the convection film on the outside of a cylindrical surface in a free medium which is about 20 per cent lower than that for the inside of a pipe and which we have used for both films. We have not distinguished between the two constants because no information is given as to the values of these constants when the cylinder is placed within the pipe. While a formula for the conduction component in a non-concentric system is given by Whitehead and Hutchings[2] it is far too complicated to use in this analysis, and it reduces substantially to the concentric formula which we have employed except for extremely small separations between the cylinders at one point. Further there is considerable experimental evidence to support the assumption that the emissivity constant is substantially unity for the types of cable surfaces employed.

Discrepancies were expected, because of the assumptions which had to be made, and because the physical location of the cables within the pipe cannot be controlled. We have used assumptions and theory only to obtain a sensible understanding of the problem with which we have to deal and to determine what simplifications can justifiably be made in order to obtain practical working expressions. These working expressions were then developed directly from actual tests rather than from theory. We do not share Mr. Burrell's desire for working expressions of sufficient complexity to identify the separate effects of the three modes of heat transfer.

Dr. Wiseman's simplified formulas for calculating h_{sd} (on a per cable basis) for three cables in an oil-filled pipe or in a gas-filled pipe at 200 pounds per square inch are very interesting and similar formulas may be derived from Figures 3 and 4 of the paper assuming that Q, P, and T_m have fixed typical values. Unfortunately Dr. Wiseman's derivation of the equivalent β in his formulas gives values which are not comparable to β as defined in this paper. The corresponding relationship for β as defined in the paper is

$$\frac{h_{sd}}{3} = \frac{0.00411\beta}{2.15D_s}$$

and this yields $\beta = 290$ for the oil-pressure system and $\beta = 450$ for the gas-pressure system.

We cannot accept his formula for the oil system since its corresponding value on a total heat flow basis is $H_{sd} = 1.15/D_s'$ which is equivalent to $Q/\Delta T = 3.9$ for $D_s' = 4.5$. None of the tests cited in Table III of the paper give any support for so high a value.

Dr. Wiseman also assumes that the overall thermal resistance varies inversely with the diameter whereas we believe that a more representative variation may be deduced from the slope of the curves of Figures 3 and 4 in the vicinity of the typical operating points. Thus for $Q = 25$ watts per foot and $T_m = 50$ degrees centigrade, we derive the simplified expressions

$$H_{sd}\text{ (oil)} = 0.70/D_s'^{1/2} \text{ thermal ohm feet} \quad (1)$$

$$H_{sd}\text{ (gas at 200 psi)} = 1.20/(D_s')^{0.7} \text{ thermal ohm feet} \quad (2)$$

The corresponding equations on a per cable basis and with three cables in the pipe are

$$h_{sd} = \frac{1.44}{\sqrt{D_s}} \text{ and } h_{sd} = \frac{2.07}{(D_s)^{0.7}} \text{ respectively}$$

Figures 3 and 4 are intended to give practical working values of β or H_{sd} over a wide range of operating conditions. Mr. Greebler is right in pointing out that the effect of temperature variations upon the radiation component is considerably greater than the effect of variations in the convection term which is the essential variant in Figure 3. The inclusion of the temperature of the medium in the working expressions would vastly complicate them, however, and as a practical matter this is unnecessary.

In all of the Greebler-Barnett data[3] it will be observed that β varies inversely as $Q^{1/4}$ within the accuracy of measurement. The dependence of β upon D_s cannot be evaluated from this data since only a single value of D_s was employed, but since the convection term theoretically varies directly as $Q^{1/4}/D^{1/4}$ we believe that the temperature variation in the radiation term which Greebler has mentioned will be accounted for with sufficient accuracy by expressing the Greebler-Barnett data for fiber and Transite ducts in the form

$$\beta\text{(fiber)} = 1120D_s^{1/4}/Q^{1/4} \text{ degrees centigrade square centimeters per watt} \quad (3)$$

$$\beta\text{(Transite)} = 990D_s^{1/4}/Q^{1/4} \text{ degrees centigrade square centimeters per watt} \quad (4)$$

This will have the effect of changing the slope of the curves when plotted in accordance with Figure 3.[4]

The corresponding values of H_{sd} assuming a working value of $Q = 10$ watts per foot are

$$H_{sd}\text{ (fiber)} = (2.59/D_s^{1/2}) + 0.33 \text{ thermal ohm feet} \quad (5)$$

$$H_{sd}\text{ (Transite)} = 2.29/D_s^{1/2} \text{ thermal ohm feet} \quad (6)$$

While further theoretical and experimental work may well be undertaken in order to clear up some of the apparent discrepancies between theory and practice and to yield more factual data on the performance of cables in duct; we agree with Mr. Kidder that little of any practical improvement in cable load ratings will result. We do not wish to discourage further efforts in this direction, but we feel that it is sufficient to base cable ratings on Figures 3 and 4 of the paper or more simply on equations (1, 2, 5, and 6) just given.

REFERENCES

1. See reference 2 of the paper.

2. CURRENT RATING OF CABLES FOR TRANSMISSION AND DISTRIBUTION, S. Whitehead, E. E. Hutchings. *Journal*, Institution of Electrical Engineers (London, England), volume 83, 1938, equation 10.3, page 531.

3. HEAT TRANSFER STUDY ON POWER CABLE DUCTS AND DUCT ASSEMBLIES, Paul Greebler, Guy F. Barnett. *AIEE Transactions*, volume 69, part I, 1950, pages 357–67.

4. Discussion by J. H. Neher of reference 3 above, pages 365–66.

ATTACHMENT 3 TO AEP:NRC:0692DF

CABLE TRAY ALLOWABLE FILL DESIGN STANDARD

[illegible]

1. In all type trays, cables shall be placed in the trays in a neat workmanship like manner. Crossing of cables shall be avoided, cable pile-ups shall be kept to a minimum and cables shall not extend above the top of the tray.

2. (a) When installing cables in a power tray place the power cables in a single layer spaced approximately 1/3 the O.D. (outside diameter of the cables) apart. See Figure 1.

   (b) The summation of the O.D. of the power cables shall not exceed 75% of the tray width. See Table 1 for maximum allowable fill.

3. When installing cables in control and instrumentation trays, the total cross sectional area of installed cables shall not exceed 40% of the tray cross sectional area. See Table 2 for maximum allowable fill.

4. When it is necessary to exceed the maximum allowable fill approval from the responsible cable engineer is required.

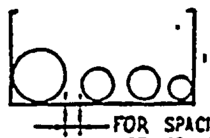


FIGURE 1

POWER CABLE SPACING

NOTES:
1. FOR CABLES OF EQUAL O.D., SPACING IS 1/3 O.D.
2. FOR CABLES OF UNEQUAL O.D. SPACING IS 1/3 O.D. OF LARGER CABLE.

TRAY WIDTH	ALLOWABLE FILL
12"	9"

TABLE 1

POWER TRAY MAXIMUM FILL

TRAY WIDTH	ALLOWABLE FILL 6" HIGH TRAY	ALLOWABLE FILL 12" HIGH TRAY
12"	28.8 in^2	57.6 in^2

TABLE 2

CONTROL & INSTRUMENTATION TRAY MAXIMUM FILL

NOTES:
1. AS TRAY FILL APPROACHES ITS ALLOWABLE LIMIT THE FIELD SHALL TAKE NOTE IF CABLES ARE REACHING OVER THE SIDES OF THE TRAY (E.G. DUE TO POORLY TRAINED CABLES). IF NECESSARY, THE FIELD, AT ITS OWN DISCRETION SHALL INSTALL CABLE TRAY SIDEBOARD PER 1-2-EDS-639 (PDS-1181).
2. IN EXTREME CASES OR WHERE SIDEBOARDS CAN NOT BE INSTALLED, THE FIELD SHALL INFORM THE ELECTRICAL PLANT SECTION TO CLOSE THE TRAY.

FOR USE IN NUCLEAR PLANT ONLY

INDIANA & MICHIGAN ELECT. CO. | D.C. COOK NUCLEAR PLANT | PDS-1191-0

ELECTRICAL PLANT DESIGN SECTION PLANT DESIGN STANDARD | REVISION-0 | CABLE TRAY ALLOWABLE FILL

APP'D [signature] | DR. NJC | CH. NJR | DATE 2-14-86

AMERICAN ELECTRIC POWER SERVICE CORP. | 1-2-EDS-642-0 | SH. 1 OF 1

ATTACHMENT 4 TO AEP:NRC:0692DF

ANALYSES AND MATHEMATICAL MODELS

This attachment includes the pertinent sections of the report on ampacity program development. The original report and the computer program were developed by the Electrical Section team members, AEPSC, New York.

APPENDIX A

THEORETICAL DEVELOPMENT OF HEAT TRANSFER PHENOMENA WITH RESPECT TO CABLE AMPACITY IN LOW FILL CABLE TRAYS

A.1 REVIEW OF BASIC HEAT TRANSFER MECHANISMS

Heat energy will flow through or from a body by means of three different mechanisms:

Conduction is the flow of heat from a point of higher temperature to a point of lower temperature, through a body or from one body to another body in contact, without significant molecular movement. The equation for one dimensional steady state thermal conduction for a solid of constant cross sectional area is [1]:

$$q_{cd} = k\,A\,\frac{\Delta T}{X} \qquad (1)$$

Where: q_{cd} = Conductive heat transfer.
k = Thermal conductivity
A = Area normal to heat transfer flow
ΔT = Temperature difference
X = Thickness of solid

Convection is the flow of heat away from the surface of a heated body by the motion of the surrounding fluid (gas or liquid). When the motion of the fluid is produced mechanically, the action is known as forced convection. When the motion of the fluid is produced by differences in the fluid density resulting from temperature differences, the action is known as natural convection.[1] The equation for heat transfer by means of natural convection is:

$$q_{cv} = h_{cv}\,A_s\,(T_s - T_a) \qquad (2)$$

Where: q_{cv} = Convective heat transfer
h_{cv} = Convective heat transfer coefficient
A_s = Surface area of the body
T_s = Surface temperature of the body
T_a = Ambient temperature of the surrounding fluid.

Any body at a temperature greater than absolute zero will lose heat in the form of radiant energy. Likewise any body will absorb heat radiated from any other heated body. The net exchange of heat is proportional to the difference of the forth power of their absolute temperatures. The net transfer of energy by radiation from a body to ambient or from a body to a surrounding body separated by a nonabsorbing medium is given by [1]:

$$q_r = \sigma \epsilon A_s \ (T_s{}^4 - T_a{}^4) \qquad (3)$$

Where:
- q_r = Radiant heat transfer
- σ = Stefan - Boltzman constant
- ϵ = Surface emissivity (a factor between zero and unity, unity being a perfect emitter or "black body")
- A_s = Surface area of radiator
- T_s = Absoluter temperature of surface of radiator.
- T_a = Absolute temperature of ambient or of surrounding body.

In actuality, the transfer of heat will be the result of the summation of conductive, convective and radiant transmission mechanisms or:

$$Q = q_{cd} + q_{cv} + q_r \qquad (4)$$

Where: Q= the total heat transfer

A.2 HEAT FLOW IN CABLE TRAYS

Presently, IPCEA Standard P-54-440 is the industry benchmark for cable ampacities in open top tray. Much of this standard is based on work done by Stolpe[2]. The ampacities presented in this standard depend heavily on the assumption that the cables are tightly packed and that there is no air flow through the cable bundle. The cable bundle is treated as a homogeneous rectangular mass with uniform heat generation. Based on the above criteria, the allowable watts per linear foot of cable tray is found to be constant for a given total cross-sectional area of cables (at a given ΔT). Referring to the fundamental equations for heat transfer outlined in the previous section, it is clear that conductive heat transfer is the governing heat transfer mechanism. That is to say, allowable heat loss is inversely proportional to the thickness (i.e., cross-sectional area) of the body through which the heat flows, for a given ΔT.

When a cable tray is filled with cables to a depth of one layer or less, the assumption can be made that each cable will be exposed to a free flow of air. In this case the above treatment of heat transfer does not apply. For low cable tray fills, convective and radiant heat transfer are the governing mechanism. If this is true, the allowable heat loss per linear foot of cable tray will be constant for a given total surface area of cables as per equations (2) and (3). The validation of the above theory which is developed in the next section is the major emphasis of this discussion.

A.3 HEAT TRANSFER PHENOMENA FOR CABLE TRAYS WITH LOW FILL

Theory: When a cable tray is filled to a depth less than or equal to one layer of cables, the maximum allowable heat loss will be constant for a given total cable surface area at constant ΔT.

An initial assumption will be made that the above theory is true. Experimental data will be used to validate this assumption. It will then be shown that the ampacity for any cable in the tray may be found based on the allowable heat loss.

The problem will be simplified by initially assuming that the tray contains only one size cable and that each cable is carrying the same current. In this analysis, per unit area refers to per unit area of cable tray.

The total cable surface area per unit area is:

$$A_s = n \pi d \qquad (4)$$

Where: A_s = Total cable surface area P.U.
n = Number of 3 Ø cables per unit area
d = Diameter of each cable P.U.

The percentage fill of the tray can be defined as the summation of the per unit cable diameters or:

$$F = nd \qquad (5)$$

Note that this differs from the industry standard of defining percentage fill based on the summation of the cables cross-sectional areas.

From examination of equations (4) and (5) it is clear that the surface area A_s will be constant for a given percentage fill F.

The total heat generated per unit area by resistive heating of the cables is:

$$Q = 3n I^2 R_{ac} \qquad (6)$$

Where: Q = Total heat generated per unit area.
I = Conductor current
R_{ac} = a.c. resistance of conductor per unit length.

Rearranging equation (5)

$$n = F/d \tag{7}$$

Substituting in equation (6)

$$Q = \frac{3F}{d} \quad I^2 \quad R_{ac} \tag{8}$$

Solving for the current

$$I = \sqrt{\frac{Q\ d}{3\ F\ Rac}} \tag{9}$$

or

$$I = \sqrt{\frac{Q}{3F}} \quad \sqrt{\frac{d}{Rac}} \tag{9a}$$

According to the initial assumption Q will be constant for a given surface area that is to say, a certain percentage fill. Therefore a plot of I vs $\sqrt{d/Rac}$ for a given percent fill should yield a straight line through the origin with slope equal to $\sqrt{Q/3F}$.

Plots of I vs. $\sqrt{\frac{d}{Rac}}$ are shown in Figure A-1 for several raceway configurations at a constant tray fill of 67%. This data was determined experimentally at AEP's Canton Test Lab (see Appendix C). As predicted, the plots are linear and pass through the origin.

The maximum allowable heat for this tray fill may be determined from the slope of the plots as shown below:

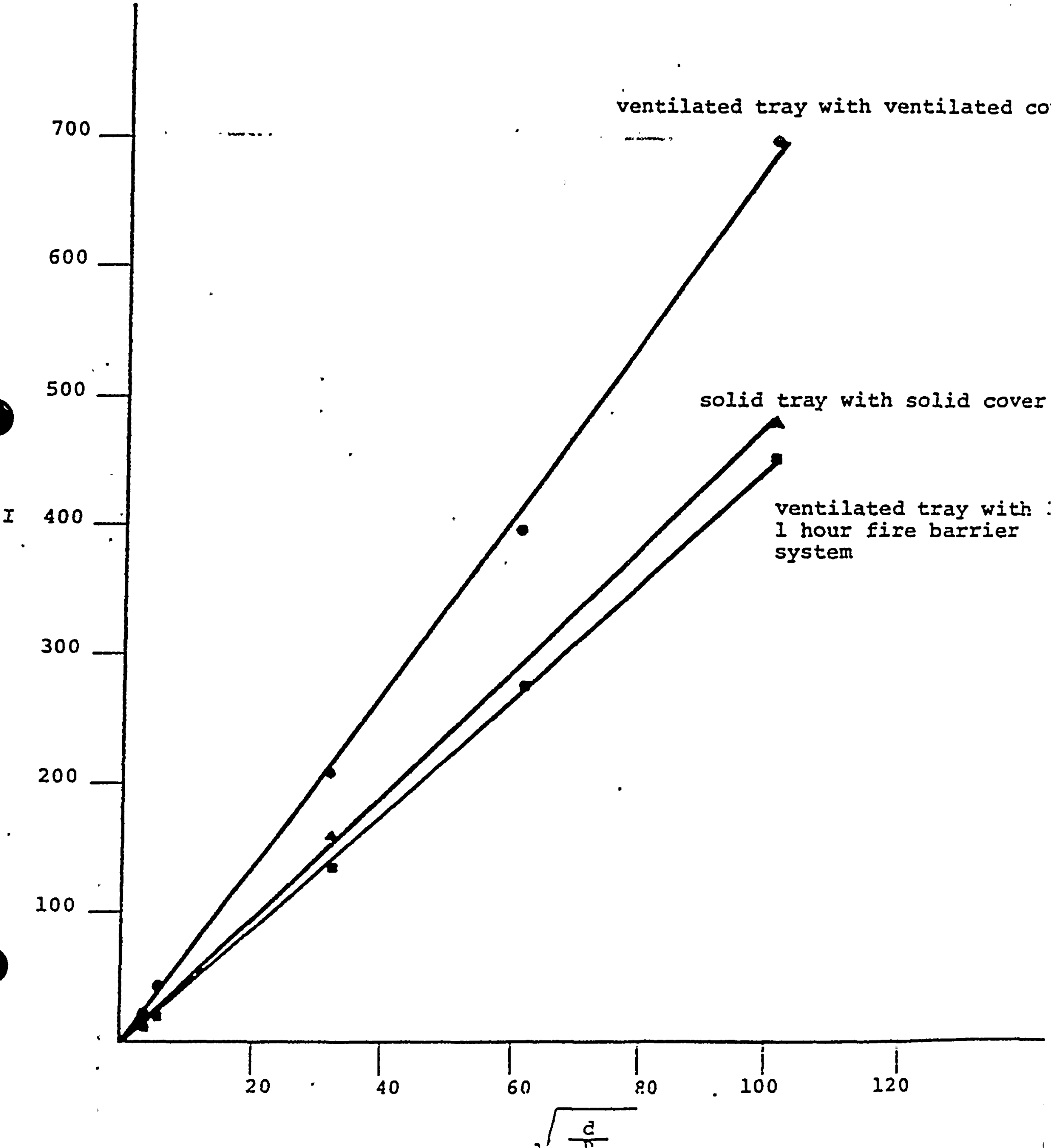
$$\left(\frac{\Delta I}{\Delta \sqrt{\frac{d}{Rac}}} \right)^2 3F = Q \tag{10}$$

A.4 CALCULATION OF AMPACITY

In the previous section it was shown that the total allowable heat, Q, was constant for a given percentage tray fill. In order to eliminate hot spots caused by locally intense heat sources, this allowable heat generation should be distributed uniformly across the occupied area of the tray.

This concept of uniform heat distribution is discussed in depth by Stolpe in Reference 2. However, whereas Stolpe's analysis required a uniform heat distribution per unit volume (for tightly packed cable trays), the calculation of ampacity for low fill trays is dependent upon a uniform heat distribution per unit area of filled tray.

FIGURE A-1



ventilated tray with ventilated co
solid tray with solid cover
ventilated tray with 1
1 hour fire barrier
system
700
600
500
400
300
200
100
I
20
40
60
80
100
120

A.4 CALCULATION OF AMPACITY (contd).

Figure A-2 illustrates the differing requirements of uniform heat distribution. As per Stolpe's analysis of tightly packed trays, seven #12 cables occupy the same volume as one 4/0 cable and thus the heat generated by the two configurations should be equivalent under uniform heat distribution conditions. For low fill trays, three #12 cables occupy the same area of tray surface as one 4/0 cable and therefore must generate the equivalent total heat. A discussion of this effect on the effective diameter of the cable group is given in Appendix B.

Keeping in mind the concept of uniform heat distribution and rearranging equation (8) it can be shown that:

$$3I^2R_{ac} = \frac{d}{F} Q \qquad (11)$$

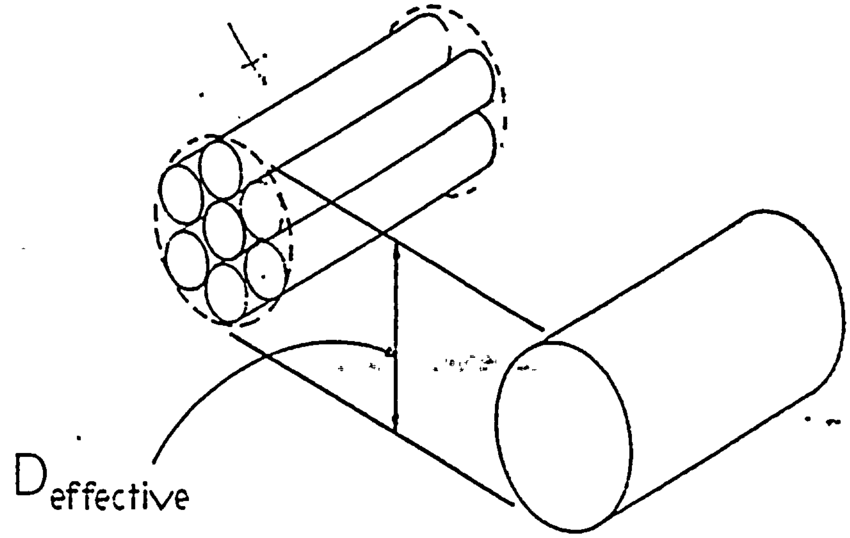
or the heat produced by the resistive heating of one three phase cable is equal to the percentage of the total allowable heat, Q, as determined by the area that cable occupies, d/F, in the cable trays.

The allowable ampacity of any cable in tray can be calculated if the allowable heat is known for a specified tray fill, from equation (9):

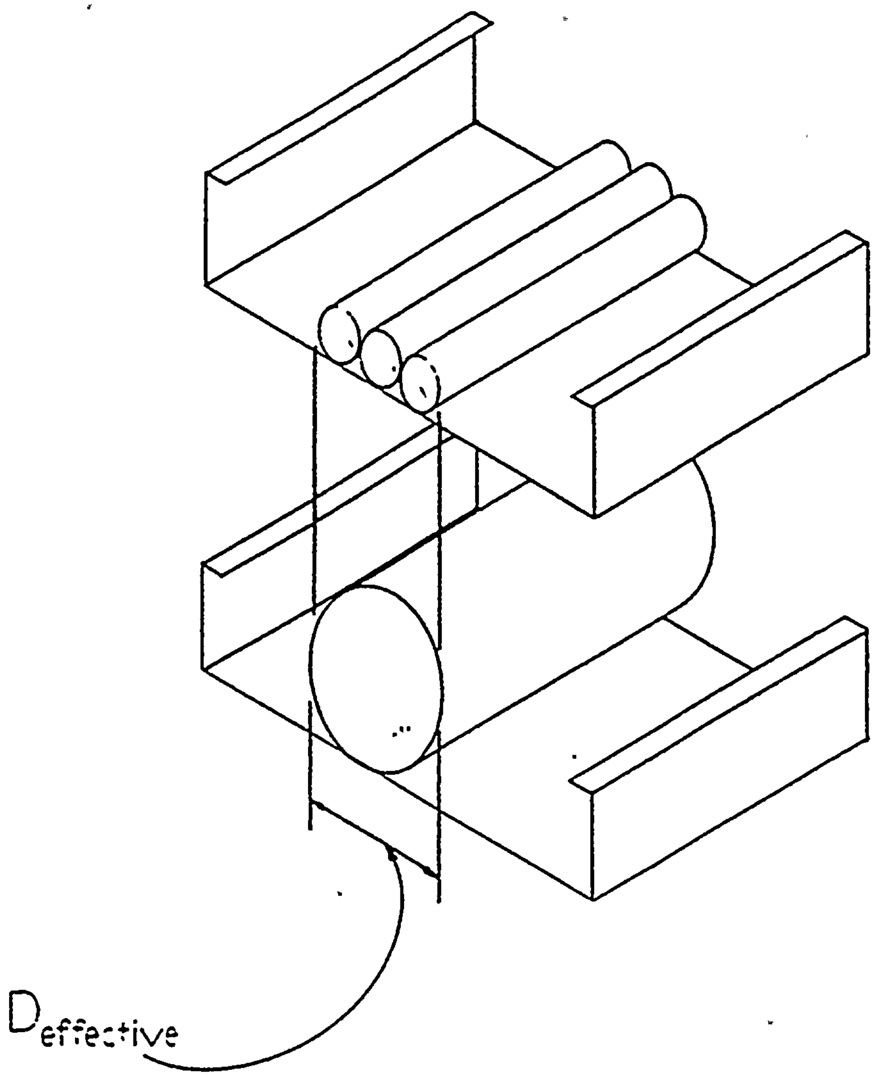
$$I = \sqrt{\frac{Qd}{3F}\, R_{ac}} \qquad (9)$$

The determination of allowable heat for various tray fills and raceway configurations is discussed in Appendix B, Computer Model.

FIGURE A-2



Equivalent heat sources for tightly packed trays as per Stolpe in Reference 2.



Equivalent heat sources for low fill cable trays

[illegible]

B.2 Program Development

The heat transmission of cables contained in a rectangular tray enclosed with multiple layers of fire barrier material is quite complex and extremely difficult to model. Therefore, an assumption was made: treat the rectangular tray and fire barriers as cylindrical sections with the equivalent surface area.

Initially, the validity of this assumption was questionable. However, because of the excellent correlation between computer data and test data, it is felt that this approximation is sound.

Utilizing the previous assumption, the program was developed based on the excellent work done by Neher and McGrath in reference 3 and Buller and Neher in reference 4.

Throughout this section, the concept of "thermal resistance" and "thermal resistivity" will be used, these terms being the inverse of thermal conductance and thermal conductivity respectively. It is often easier to visualize thermal resistance analogous to resistance in an electrical circuit, with the thermal resistance of each medium being in series, and with the conductive, convective and radiant resistance acting in parallel through each medium. A typical thermal circuit is shown in Fig. B1.

The equation for load capability as developed in reference 3 is given by the following equation:

$$I = \sqrt{\frac{T_c - (T_a + \Delta T_d)}{R_{dc}(1 + Y_c)\,\bar{R}_{ca}'}} \tag{12}$$

in equation (12)

I = conductor current (kiloamps)

T_c = conductor temperature ($^{\circ}C$)

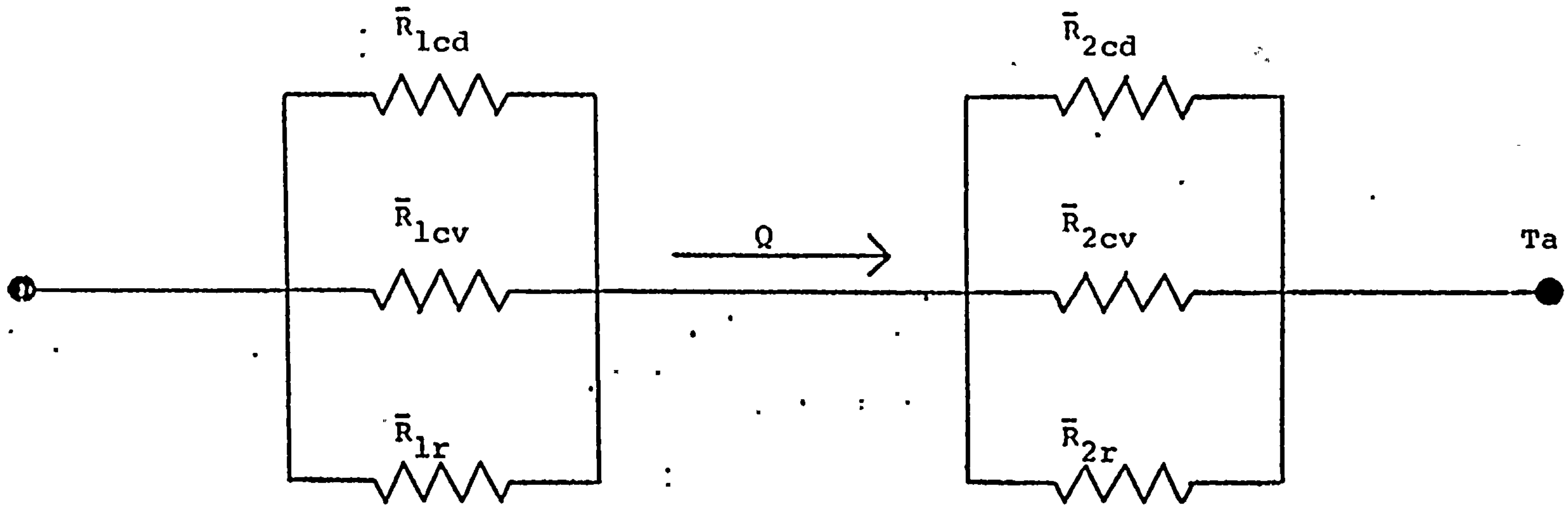
T_a = ambient temperature ($^{\circ}C$)

ΔT_d = dielectric losses in conductor ($^{\circ}C$)

R_{dc} = D.C. resistance (microhms/ft.)

Y_c = increment of ac/dc ratio

$\bar{R}_{ca}'$ = effective thermal resistance conductor to ambient (thermal ohms-ft.)



$$T_c - T_a = Q(\bar{R}_1 + \bar{R}_2)$$

where: Tc = conductor temperature (typically 90°C)

Ta = ambient temperature (typically 40°C)

Q = heat energy (watts p.u.)

$$\frac{1}{\bar{R}_1} = \frac{1}{\bar{R}_{1cd}} + \frac{1}{\bar{R}_{1cv}} + \frac{1}{\bar{R}_{1r}}$$

$$\frac{1}{\bar{R}_2} = \frac{1}{\bar{R}_{2cd}} + \frac{1}{\bar{R}_{2cv}} + \frac{1}{\bar{R}_{2r}}$$

($\bar{R}$ in thermal ohm p.u.)

In the above thermalcircuit the conductive, convective and radiant thermal resistance components through each medium are added in parallel. The equivalent thermal resistance of each medium, $\bar{R}_1$ and $\bar{R}_2$ are added in series.

FIGURE B-1

B.2.1 Determination of Electrical Resistance

The D.C. resistance of a conductor may be found from the following expression:

$$R_{dc} = \frac{1.02}{CI} \rho_c \left[(\tau + T_c)/(\tau + 20)\right]$$

where: ρ_c = electrical resistivity of conductor (circular MIL OHMS/FT at $20^{\circ}C$)

CI = circular inch area

τ = inferred temperature of zero resistance ($^{\circ}C$)

The factor $1 + Y_c$ may be determine if the ac/dc ratio is known

$$R_{ac}/R_{dc} = 1 + Y_c + Y_s + Y_p \qquad (14)$$

where: Y_s = increment of ac/dc ratio at shield

Y_p = increment of ac/dc ratio at pipe or conduit

Y_s will be zero provided shields are open-circuited and Y_p will be negligable in light of the fact that most cables in a tray will be three phase twisted conductor. Therefore equation (14) reduces to

$$R_{ac}/R_{dc} = 1 + Y_c \qquad (14a)$$

B.2.2 Determination of Thermal Resistance

If shield and pipe losses are neglected as previously discussed, the total thermal resistance conductor to ambient, R_{ca} will be the summation of the individual thermal resistances of each medium (i.e., insulation, jacket, air space, etc.).

The thermal resistance of the insulation may be calculated by the following[3]:

$$\bar{R}_i = 0.012 \bar{\rho}_i \log (D_i/D_c) \qquad (15)$$

where: $\bar{R}_i$ = thermal resistance of insulation (thermal ohms-ft.)

$\bar{\rho}_i$ = thermal resistivity ($^{\circ}C$ - CM/watt)

D_i = diameter over insulation (IN.)

D_c = diameter of conductor (IN.)

The thermal resistance through relatively thin cylinders (i.e., cable jacket, tray, fire barrier) may be calculated from the following equation[3]:

$$\bar{R} = 0.0104 \bar{\rho}\ n' \left(\frac{t}{D-t}\right) \qquad (16)$$

where: $\bar{R}$ = thermal resistance of the section (thermal ohms-ft.)

$\bar{\rho}$ = thermal resistivity of the section (^{o}C - CM/WATT).

n' = number of conductors contained within the section.

t = thickness of the section (IN.)

D = outside diameter of the section

The heat transfer between surfaces separated by a "dead-air" space involves the mechanisms of conduction convection and radiation. Each corresponding thermal resistance must be added in parallel to obtain the effective thermal resistance. However, in this case it is simplier to take the inverse of the conductances added in series. Using the equations developed in reference 4:

$$C_{cd} = \frac{q_{cd}}{\Delta T} = \frac{0.0213}{\log (D''/D')} \qquad (17)$$

$$C_{cv} = \frac{q_{cv}}{\Delta T} = 0.092 \frac{D^{1/4} \Delta T^{1/4} P^{1/2}}{1.39 + D'/D''} \qquad (18)$$

$$C_r = \frac{q_r}{\Delta T} = 0.102\, D' \epsilon\, (1 + 0.016\, T_m) \qquad (19)$$

where: C = thermal conductance due to conduction, convection and radiation respectively (watts/^{o}C-ft)

q = respective heat loss (watts/ft)

ΔT = temperature drop through the air space (

D' = outside diameter of inner surface (IN.)

D" = inside diameter of outer surface (IN.)

P = pressure of air (ATM.)

ϵ = surface emissivity of inner surface

T_m = mean temperature of air space (^{o}C)

At this point, some clarification is necessary concerning the equivalent diameter of the cable or cable group, the equivalent diameter of a 3 twisted conductor cable is obtained by multiplying the individual cable diameters by 2.15. This factor will act to increase the calculated thermal resistance which is what would be expected due to the close spacing of a 3TC cable.

The effective diameter of the cable bundle should be obtained by multiplying the effective cable diameter (or jacket diameter) by the number of three phase cables in the tray. This will be D' when calculating the thermal resistance of the air space inside the tray. The effect is to use the cable surface area to calculate the heat loss, which is in accordance with the theory discussed in Appendix A.

The thermal resistance per conductor will be the total number of conductors divided by the total thermal conductance. If 1 atmosphere pressure is assumed the thermal resistance of the air space will be given by the expression.

$$\overline{R} = \frac{n'}{C} = n' / \left[\frac{0.0213}{\log (D''/D')} + 0.092 \frac{D'^{3/4} \, \Delta T^{1/4}}{1.39 + D'/D''} + 0.102 D' \epsilon (1 + 0.0167 \, Tm) \right] \quad (20)$$

The thermal resistance from the last surface to ambient, in still air can be found from the following equation derived in reference 3.

$$\overline{R} = \frac{15.6 \; n'}{D''' \left[(\Delta T / D''')^{1/4} + 1.6 \epsilon (1 + 0.0167 \; Tm) \right]} \quad (21)$$

where: D''' = outside diameter of outer surface

As previously stated, the total thermal resistance conductor to ambient, $\overline{R}'_{ca}$ will be the summation of the individual thermal resistances through each medium.

B.2.3 Determination of dielectric losses

From reference 3:

$$T_d = W_d \quad \overline{R}'_{da} \quad (22)$$

where: W_d = dielectric loss

$\overline{R}'_{da}$ = thermal resistivity based on individual thermal resistivities at unity power factor.

$$W_d = \frac{0.00276 \; E^2 \epsilon_r \; \cos \phi}{\log D_i} \quad (23)$$

where: E = phase to neutral voltage (KV)

ϵ_r = specific inductive capacitance of insulation

$\cos \phi$ = power factor of insulation

D_i = diameter of insulation (in.)

$$\overline{R}_{da'} = \overline{R}_{ca'} - \overline{R}_i/2 \tag{24}$$

B.3 Fire Barrier Ampacity Derating (FBAD2)

The program FBAD2 was developed according to the criteria outlined in section B.2. A program listing is included in section B.4.

When running the program for cables in ventilated tray with covers, enclosed in Fire Barrier Material it was determined that the thermal effects of the tray was insignificant and could be neglected. This agreed with the results of tests at Canton (see Appendix C).

When a ventilated tray without a cover is enclosed in a Fire Barrier material, the thermal resistance introduced by the tray is negligable. Therefore the tray should not be input as a "layer" in the program.

The assumptions used to develop this program require that the tray be filled to less than or equal to one layer of cables. Therefore the number of circuits entered multiplied by the cable diameter should be less than or equal to the tray width.

When entering "N" the number of layers, the cable insulation and jacket should not be entered as a layer. The program is designed to account for their effect.

B.3.1 Data Input

The data required for running the program is as follows:

N = The number of layers of material enclosing the cable. See B.3

D (I) = The equivalent diameter of layer I in inches.

T (I) = The thickness of layer I in inches.

S (I) = The dead air space outside of layer I in inches. Enter "1" if the air space is ambient air. Note: Enter '1" <u>only</u> for ambient air.

E (I) = The emissivity of surface I. The emissivity is a number less than or equal to 1, used to determine the radiant losses, 1 being a perfect radiator (black body). See reference 1 for additional information.

P (I) = The thermal resistivity of layer I in ^{o}C-cm/watt.

<u>Note</u>: The variables D(I), T(I), S(I), E(I) and P(I) shall be entered for <u>each</u> layer input.

T1 = Conductor temperature in ^{o}C.

T2 = Ambient Temperature in ^{o}C.

P = Electrical resistivity of the conductor in circular mil ohms per foot. See Reference 3.

TO = Inferred temperature of zero resistance for the conductor material. See Referenec 3.

V = Line to line voltage in KV.

E1 = Specific inductive capacitance of the insulation. See Reference 3.

F1 = Power factor of the insulation.

T5 = Thickness of the cable jacket in inches.

P5 = Thermal resistivity of the cable jacket in ^{o}C-cm/watt.

N1 = The number of conductors per cable.

C = Area of the conductor in circular inches.

DO = The conductor diameter in inches.

DI = The insulation diameter in inches.

P1 = The thermal resistivity of the insulation in ^{o}C-cm/watt.

A = The AC/DC ratio

E5 = The emissivity of the cable surface.

D5 = The diameter of the cable in inches. -

B.4 Computer printout: FBAD2

B.4.1 The program FBAD2 is stored in the Warner Computer System under the access code for Electrical Plant Design Section.

B.4.2 Program Listing:

References

1. Heat Transmission, W.H. McAdams. McGraw-Hill Book Company, New York, N.Y., second edition, 1942.

2. "Ampacities for Cables in Randomly Filled Trays," J. Stolpe. IEEE Transactions, Paper 70 TP 557 PWR.

3. "The Calculation of the Temperature Rise and Load Capability of Cable Systems," J.H. Neher and M.H. McGrath. AIEE Transactions, Paper 57-660.

4. "The Thermal Resistance Between Cables and a Surrounding Pipe or Duct Wall," F.H. Buller and J.H. Neher. AIEE Transactions, Paper 50-52. Appendix 1.

5. "Engineering Data for Copper and Aluminum Conductor Electrical Cables," The Okonite Company. Okonite Bulletin EHB-78. Pg. 5.

6. "~~Drating~~ Derating cables in Trays Traversing Firestops or Wrapped in Fireproofing," O.M. Esteves. IEEE Transactions Paper 82 JPGC 601-3.

7. "Ampacities Cables in Open-top Cable Trays," IPCEA - NEMA Standards Publication. IPCEA Pub. No. P-54-440 (Second Edition); NEMA Pub. No. WC 51-1975.

8. Industrial Heat Transfer, Alfred Schack, Dr. - Ing. John Wiley & Sons, Inc. 1933. Pg. 180.

9. TSI response to AEP questionaire from Marilyn Grau to R.H. Bozgo dated September 29, 1982.

ATTACHMENT 5 TO AEP:NRC:0692DF

REPRESENTATIVE AMPACITY DERATING CALCULATION RESULTS

TABLE I

COMPUTER ANALYSIS OF ALLOWABLE HEAT AND CABLE AMPACITY

APPENDIX R TRAYS

Cable Tray: 1AZ-P8

Total Heat Generation Per Foot of Raceway:

Calculated Allowable: 36.98 Watts/Ft.

Actual: 9.70 Watts/Ft.

Cable No.	Cable Type	Connected Load Full Load Amps	Calculated Allowable Ampacity
1470 R	3 TC #12 CU	3.8	21.58
1469 R	3 TC #12 CU	16.0	21.58
8067 R	3 TC #12 CU	1.2	21.58
8024 R	3 TC #12 CU	1.1	21.58
8187 R	3 TC #12 CU	17.0	21.58
8026 R	3 TC #12 CU	2.7	21.58
8027 R	3 TC #12 CU	1.2	21.58
2349 R	3 TC #12 CU	1.9	21.58
*1476 R	3 TC #12 CU	-----	-----
1488 R	3 TC #12 CU	20.0	21.58
1991 R	3 TC #2 AL	60.0	90.67
16666 R-2	3 TC #12 CU	2.5	21.58

*CABLE CUT IN TRAY AND TAPED

DC-D-1035.3E-1.5 Rev. 1

POWER TRAY 1AZ PB

Rev. 1

CABLE NO.	CABLE TYPE	OD"	EQUIP. ID	H.P. KW. KVA.	FLA		ALLOW. AMP.	ALLOW. AMP.	
1470 R	3TC#12AWG CU	0.32	SPENT FUEL PIT SKIMMER PP MTR	3 HP	3.8A		21.58	21.65	
1469 R	3TC#12AWG CU	0.32	EVAPORATOR COIL DRAIN PP "W"	15 HP	16A		21.58	21.65	
8067 R	3TC#12AWG CU	0.32	VA 1MO-221	1 HP	1.2A		21.58	21.65	
8024 R	3TC#12AWG CU	0.32	VA 1MO-204	0.7HP	1.1A		21.58	21.65	
8187 R	3TC#12AWG CU	0.32	VA 1CM-321	12.8HP	17A		21.58	21.65	
8026 R	3TC#12AWG CU	0.32	VA 1MO-911	2.1HP	2.7A		21.58	21.65	
8027 R	3TC#12AWG CU	0.32	VA QMO-201	1HP	1.2A		21.58	21.65	
2349 R	3TC#12AWG CU	0.32	FUEL HANDLING AREA FAN 12-HV-AFS-4 MTR	1.5HP	1.9A		21.58	21.65	
1476 R	3TC#12AWG CU	0.32	CABLE CUT IN TROUGH & TAPED	—	—		—	—	
1488 R	3TC#12AWG CU	0.32	WASTE EVAP FEED PP "S" (TEMP)	20HP	20A		21.58	21.65	
1991 R	3TC#2AWG AL	0.92	SPLICE BOX FOR WELDING	60HP	60A		90.67	89.70	
16666 R-2	3TC#12AWG CU	0.32	MOTOR COLLECT TANK PUMP #2	2.4HP	2.5A		21.58	21.65	
		4.12"							

TABLE III

COMPUTER ANALYSIS OF ALLOWABLE HEAT AND CABLE AMPACITY

APPENDIX R CONDUIT

CABLE NO.	CONDUIT SIZE	CABLE TYPE	CONNECTED LOAD FLA	CONNECTED LOAD WATTS/FT	CALCULATED AMPACITY	ALLOWABLE WATTS/FT
*8003 R-1	4"	3 TC #2 SH-AL	57.5	3.32	99.04	9.86
*8004 R-1	4"	3 TC #2 SH-AL	64.6	4.20	99.04	9.86
*8004 G-1	4"	3 TC #2 SH-AL	64.6	4.20	99.04	9.86
8026 R-1	0.5"	3 TC #12 CU	2.7	.045	25.85	4.14
8505 R-1	1"	3 TC #12 CU	2.6	.042	25.85	4.14
8506 R-1	1"	3 TC #12 CU	2.6	.042	25.85	4.14
*8003 R-2	4"	3 TC #2 SH-AL	57.5	3.32	99.04	9.86
*8004 R-2	4"	3 TC #2 SH-AL	64.6	4.20	99.04	9.86
*8004 G-2	4"	3 TC #2 SH-AL	59	3.50	99.04	9.86
8154 G-2	1"	3 TC #12 CU	2.6	.042	25.85	4.14
8155 G-2	1"	3 TC #12 CU	2.6	.042	25.85	4.14
*8744 R-2	4"	3 TC #2 SH-AL	71.9	5.20	99.04	9.86

*5KV CABLE

NOTES:
1. ALL CABLES ARE 600V EXCEPT AS NOTED.
2. CABLE FLA (FULL LOAD AMP) AND AMPACITY IS GIVEN IN AMPS.
3. AMBIENT TEMPERATURE WAS TAKEN TO BE 40° C.

DC-D-1035. 3E-6.3 Rev. 1

APPENDIX "R" CONDUITS

* 5KV
/ CALC. FLA.
– MFR. DWG. FLA.

Rev. 1

	CDT. SIZE	CABLE NO.	CABLE TYPE	O.D. INCHES	EQUIPMENT ID	HP KW KVA	FLA		ALLOW AMP	ALLOW AMP.	REF. DWG.	
1	4"	8003 R	*3 TC #2 SH AL	1.14	RSDL HT RMVL Pp 1W MTR	400 HP	57.5A		99.04	94.45		1
2	4"	8004 R	*3 TC #2 SH AL	1.14	ESS SRVC WTR Pp 1W MTR	450 HP	64.6A		99.04			2
3	4"	8004 G	*3 TC #2 SH AL	1.14	ESS SRVC WTR Pp 1E MTR	450 HP	64.6A		99.04			3
4	1/2"	8026 R	3 TC #12 AWG CU	0.32	VALVE TMC-911	2.1 HP	2.7 A		25.85		1-1320	4
5	1"	8505 R	3 TC #12 CU	0.32	EQ TF Pp 1-AB-2	2.0 HP	2.6 A		25.85		1-1320	5
6	1"	8506 R	3 TC #12 CU	0.32	EQ TF Pp 1-AB-1	2.0 HP	2.6 A		25.85		1-1320	6
8	4"	8003 R	*3 TC #2 SH AL	1.14	RHP 2W	400 HP	57.5A		99.04		2-1328	8
9	4"	8004 R	*3 TC #2 SH AL	1.14	ESWP "2W" MR	450 HP	64.6A		99.04		2-1328	9
10	4"	8004 G	*3 TC #2 SH AL	1.14	ESWP "2E" MR	450 HP	59 A		99.04		2-1328	10
11	1"	8154 G	3 TC #12 CU	0.32	EQ TF PP 2CD1	2.0 HP	2.6 A		25.85		2-1320	11
12	1"	8155 G	3 TC #12 CU	0.32	EQ TF PP 2CD2	2.0 HP	2.6 A		25.85		2-1320	12
13	4"	8744 R	*3 TC #2 SH AL	1.14	AUX. FD. PP	500 HP	71.9 A		99.04		2-1328	13

ATTACHMENT 6 TO AEP:NRC:0692DF

RESULTS FROM TEST REPORT #CL-542

For information of AEP System employees only.

TEST REPORT

American Electric Power Service Corp.
Canton Laboratory
P.O. Box 487 Canton, Ohio 44701

Title: AMPACITY TEST FOR POWER CABLES	Test No. CL-542 Date December 16, 1983
Test By: L.J. Balanti;J. P. McCallin Report By: L. J. Balanti Approved By: A. P. Litsky	Made For: AEPS Corp. Sponsor: W. F. Wilson - New York Test Completed: November 18, 1983

I. INTRODUCTION

For compliance with 10CFR50, Appendix R at the D. C. Cook Nuclear Plant, tests were conducted on power and control cables enclosed in a TSI, Inc. one-hour fire barrier system. The results of the test will be compared to computer-generated data to determine the validity of the computer model on heat run flow and cable ampacity.

II. OBJECTIVE

The test objective was to simulate as closely as possible the actual conditions of tray and conduit runs proposed for Cook Plant and determine the final conductor temperature for the specified amperage and tray fill.

III. TEST METHOD

The generalized test method consisted of:

1. Installing cables.
2. Attaching thermocouples.
3. Enclosing the TSI fire barrier system.
4. Applying the specified amperages.
5. Maintaining a constant ambient temperature of 40°C.
6. Monitoring the temperature rise and final conductor temperature.

Copies To:

T. O. Argenta/B. R. Larson - Canton
B. J. Ware - Columbus
C. B. Charlton - Canton
T. E. King - Columbus
S. R. Kekane - Columbus

I. TEST METHOD (Cont'd.)

The detailed test procedure was as follows:

1. Equipment

1.1 Cable Tray and Cover

1.1.1. Cable tray was galvanized steel, expanded metal bottom; size 12" x 6" x 8'-0" Long.

1.1.2. Cable tray cover was galvanized steel, ventilated 12" wide.

1.1.3. 10'-0" Original tray length cut to 8'-0" to accommodate installation in environmental chamber.

1.1.4. Tray cover attached to tray by using #10 x 3/8" Parker-Kalon type B (Z) with "H" head.

1.2. Conduit

1.2.1. 4" I.D. Galvanized rigid steel.

1.2.2. 1" I.D. Thinwall EMT

1.2.3. Conduits cut to 8'-0" to conform with cable tray length and installation in chamber.

1.3 Fire Barrier Envelope

1.3.1. Thermo-Lag 330-1 subliming coating manufactured by TSI, Inc. for a one hour barrier. Thickness of barrier was .500" (+.125", -.000").

1.3.2. Prefabricated panels 6'-0" x 4.6".

1.3.3. Prefabricated conduit sections.

1.3.4. Steel banding.

1.4. Cables

The following cables were used for testing:

B/M Item #	Description
324	3TC #12 Cu 600 V
339	3TC #6 Al 600 V
344	3TC #4 Al 600 V
348	3TC #2 Al 600 V
3101	3TC #4 Al 5 kV shielded
3102	3TC #2 Al 5 kV shielded
3103	3TC #2/0 Al 5 kV shielded
3104	3TC #4/0 Al 5 kV shielded
3120	4/C #12 Cu 600 V.

2. Test Setup

2.1 Raceway

2.1.1. Cable tray and conduit were supported approximately 2'-6" above floor to allow for natural ventilation.

2.1.2. Raceway ends were sealed during the test with thermal insulating material to prevent heat loss through these areas.

Note:

This procedure could cause excessive heating of the cables passing through the thermal seal; therefore, all temperature readings were taken a minimum of 1'-0" from the thermal seal.

2.2 TSI One Hour Fire Barrier System

2.2.1. The tray envelope was constructed of the prefabricated panels, cut so as to fit as shown in the Appendix (see Figure #1).

2.2.2. The conduits were encased in the prefabricated sections.

2.3 Thermocouples

2.3.1. T-Type thermocouples were used to measure temperatures of the following:

A. Ambient air
B. Top and bottom of the fire barrier envelope
C. Air space in tray
D. Conductors.

2.3.2. Thermocouples were installed on the inward side of the conductor in a triplex arrangement (see Figure 2). A hole was bored in the insulation and the thermocouples were placed on the conductor.

2.3.3. Thermocouples were imbedded in Omegatherm 201 high thermal conductivity paste.

2.3.4. Thermocouples were installed in a position located on the cables in the center of the tray where:

A. Heat generation is greatest.
B. Heat dissipation is the least (see Figure 3).

2.3.5. The minimum number of thermocouples used to measure the conductor temperature was two (2) per cable circuit installed in the tray and five (5) for single cables installed in the conduit.

2.4. Cables

2.4.1. Cables were positioned in the cable tray in a single layer in such a position that there was a minimum spacing of 1/3 the diameter of the larger adjacent cable. Cables were then secured with "Ty-Raps".

3. Test Procedure

3.1 Each test consisted of installing the cables in the tray in one of six (6) configurations as specified in the test request.

3.2 Once the proper setup was attained, cables were subjected to a load of three phase, 60 Hz sinusoidal current as specified in Section 4.

3.3 Ambient temperature was set to 40°C.

3.4. Temperature rise of the cables was recorded on an Esterline Angus Model PD-2064 data acquisition system at ½-hour intervals until the cable temperatures stabilized.

3.5. The voltage and amperage of each circuit was monitored periodically throughout the test.

4. Test Configurations

4.1 Test #1

Circuit No.	Item No.	Description	Runs in Tray	Ampacity
1	324	3TC#12 Cu	7	3.8
2	324	3TC#12 Cu	3	20.0
3	348	3TC#2 Al	1	60.0
4	324	3TC#12 Cu	1	0

:

2.3.5. The minimum number of thermocouples used to measure the conductor temperature was two (2) per cable circuit installed in the tray and five (5) for single cables installed in the conduit.

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2	324	3TC#12 Cu	3	20.0
3	348	3TC#2 Al	1	60.0
4	324	3TC#12 Cu	1	0

4.2 **Test #2**

Circuit No.	Item No.	Description	Runs in Tray	Ampacity
1	324	3TC#12 Cu	2	.17
2	324	3TC#12 Cu	2	.71
3	324	3TC#12 Cu	4	2.8
4	348	3TC#12 Cu	1	6.8
4	3120	4/C#12 Cu	1	6.8
5	344	3TC#4 Al	1	53.0

4.3 **Test #3**

Circuit No.	Item No.	Description	Runs in Tray	Ampacity
1	324	3TC#12 Cu	5	.71
2	324	3TC#12 Cu	5	2.8
3	3120	4/C#12 Cu	1	6.8
3	324	3TC#12 Cu	2	6.8
4	3120	4/C#12 Cu	2	16.0
4	324	3TC#12 Cu	2	16.0
4	339	3TC#6 Al	1	16.0
5	339	3TC#6 Al	1	36.0
5	344	3TC#4 Al	1	36.0
6	344	3TC#4 Al	1	53.0
7	348	3TC#2 Al	2	60.0
8	324	3TC#12 Cu	1	0

4.4 **Test #4**

Cable Size: 3TC#12 Cu 600 V.
Conduit Size: 1" I.D. EMI
Ampacity: 2 amps.

4.5 **Test #5**

Cable Size: 3TC#2 Al 5 kV shielded with one end grounded.
Conduit Size: 4" I.D. Galv. rigid.
Ampacity: 72 amps.

4.6 **Test #6**

Circuit No.	Item No.	Description	Runs in Tray	Ampacity
1	3101	3TC#4 Al Sh.	2	20
2	3102	3TC#2 Al Sh.	2	25
3	3103	3TC#2/0 Al Sh.	2	40
4	3104	3TC#4/0 Al Sh.	1	50

IV. TEST RESULTS

The complete temperature recordings are tabulated along with test comments on computer printouts and listed under data sheets in the Appendix.

The final conductor temperatures for each test are listed below:

Test No.	Cable	Ampacity (Amps)	Runs in Tray	Highest Conductor Temperature (°C)
1	3TC#12 Cu	3.8	7	45.6
	"	20.0	3	59.7
1	3TC#2 Al	60.0	1	55.7
2	3TC#12 Cu	.17	2	42.6
	"	.71	2	42.7
	"	2.8	4	45.1
	"	6.8	1	44.4
2	4/C#12 Cu	6.8	1	43.9
2	3TC#4	53.0	1	58.3
3	3TC#12 Cu	.71	5	54.6
	"	2.8	5	57.9
	"	6.8	2	60.4
	"	16.0	2	67.3
3	4/C#12 Cu	6.8	1	55.2*
	"	16.0	2	62.7*
3	3TC#6 Al	16.0	1	57.6
	"	36.0	1	65.9*
3	3TC#4 Al	36.0	1	57.9*
	"	53.0	1	68.8
3	3TC#2 Al	60.0	2	63.7
4	3TC#12 Cu	2.0	1	42.9
5	3TC#2 Al	72.0	1	65.0
6	3TC#4 Al	20	2	45.6
6	3TC#2 Al	25	1	45.4
6	3TC#2/0 Al	40	2	45.5
6	3TC#4/0 Al	50	1	44.5

* Thermocouple installed on insulation, not conductor.

V. DISCUSSION

Due to a limited supply of variable power sources, several circuits were consolidated. In all cases, the loads were met or exceeded those that were originally requested.

As per the original request, conductors were placed in the cable tray in a single layer in such a position that there was a minimum spacing of 1/3 the diameter of the larger adjacent cable. Although this probably is not the best simulation of actual conditions, it was one criterion of the test request. During Test #3, the amount of cables made it impossible to follow this criterion. It was followed as closely as possible and the results can be viewed in the Appendix under "Photographs".

All results contained in this report were forwarded to W. F. Wilson, New York, immediately upon completion of the test. Any questions pertaining to the actual test results as compared to the computer-generated data should be directed to him.

VI. APPENDIX

A. Data sheets
B. Test setup
C. Photographs.

COMMENTS - TEST No. 1

1.) TEST 1 CL 542 11/01/83 TIME IS 4:20 A.M.
2.) START A=.785V B=.798V C=.810V, ALL 3.8 AMP
3.) START A=.732V B=.657V C=1.02V, ALL 60 AMP
4.) START A=1.17V B=1.34V C=1.19V, ALL 20 AMP
5.) CHANNEL 39= AMBIENT
6.) CHAN 2=TRAY TOP,3=TRAY BOTTOM,4=AIR IN TRAY
7.) CHANNEL 6,7 ARE ON 60 AMP CIRCUIT
8.) CHANNEL 5,8 ARE ON 20 AMP CIRCUIT
9.) ALL OTHER CHANNELS ON 3.8 AMP CIRCUIT
10.) CURR END A 3.9 B 3.9 C 3.9
11.) VOLT END A .870 B .845 C .867
12.) CURR END A 59.2 B 59.5 C 59.3
13.) VOLT END A .816 B .713 C 1.03
14.) CURR END A 20.4 B 20.3 C 20.2
15.) VOLT END A 1.238 B 1.410 C 1.259
16.) END TEST #1 CL-542 11/1/83

TEST No. 1

ESTERLINE ANGUS DATA

TIME	CH#0	CH#2	CH#3	CH#4	CH#5	CH#6	CH#7	CH#8	CH#9	CH#11	CH#12
04:20	17.3	25	25.3	25.7	25.5	25.6	25.6	25.3	25.5	25.6	25.6
04:45	19.4	33.4	35	28.9	43.4	36.4	35.7	43.3	29.8	29.3	29.2
05:15	21	37.2	38.1	34.1	49.5	44.1	43.2	49.8	35.4	35	34.5
05:45	23	39	39.5	38.7	53.5	48.9	48	53.9	39.5	39	38.5
06:15	24.8	40.4	41	41.6	55.9	51.7	50.4	56.1	41.9	41.2	40.8
06:45	26.4	40.5	40.7	43.3	57.3	53.5	52.4	57.6	43.3	42.5	42.1
07:15	27.5	41.2	41.2	44.1	57.8	54.4	53.3	58.2	44.2	43.2	42.8
07:45	28.2	40.8	40.7	44.6	58.8	54.9	53.9	59.2	44.4	43.3	43.2
08:15	28.7	41.3	41.4	44.8	58.6	54.8	53.6	59	44.4	43.6	43.2
08:45	29.2	41.4	41.9	45.4	58.9	55.2	54	59.2	44.7	43.8	43.5
09:15	29.5	41.3	42.1	45.5	59.1	55	54.1	59.3	44.8	44	43.7
09:45	29.8	41.1	41.8	45.6	59.1	55.3	54.1	59.3	44.9	44.1	43.7
10:15	30	41.1	41.6	45.8	59	55.5	54.4	59.2	44.9	44.1	43.8
10:45	30.2	41.4	42.1	45.6	59.2	55.3	54.3	59.4	44.9	44.3	43.7
11:15	30.3	41.6	42.3	45.8	59.3	55.3	54.2	59.5	45	44.2	43.8
11:45	30.5	41.6	42.5	45.9	59.7	55.5	54.6	59.5	45.2	44.2	43.9
12:15	30.6	41.2	41.9	45.9	59.3	55.6	54.5	59.4	45.2	44.1	44
12:45	30.9	41.2	41.8	45.9	59.2	55.6	54.5	59.2	45.3	44	44.1
13:15	31	41.5	42.1	46	59.3	55.6	54.6	59.4	45.4	44.2	44.1
14:15	31.1	41.6	42.3	45.9	59.3	55.6	54.5	59.3	45.3	44	44.1
14:45	31.1	41.5	42.3	45.9	59.7	55.5	54.6	59.6	45.2	44.3	43.9
15:15	31.1	41.2	41.9	45.9	59.4	55.6	54.6	59.4	45.4	44.2	44.1
15:45	31.2	41.2	41.9	46	59.5	55.7	54.5	59.5	45.4	44.2	44.1

TIME	CH#17	CH#18	CH#20	CH#25	CH#26	CH#27	CH#28	CH#36	CH#37	Ambient CH#39
04:20	25.5	25.5	25.5	25.6	25.6	25.6	25.7	25.6	25.8	24
04:45	29.2	29.8	29.2	29.4	30.2	30.1	30	29.3	30.9	37.9
05:15	34.6	35.6	34.7	35	35.9	36.1	36	34.6	37	40.8
05:45	38.6	39.5	38.7	38.9	39.9	40.1	40.2	38.4	41.1	40.4
06:15	40.6	41.4	41.1	41	42.1	42.3	42.5	40.8	43.4	40.8
06:45	42	42.6	42.2	42.4	43.2	43.4	43.9	42.1	44.8	40.2
07:15	42.6	43.1	42.9	43.1	44	44.1	44.5	42.9	45.5	41
07:45	42.8	43.5	42.9	43.1	44.4	44	44.8	43.2	45.5	40.4
08:15	42.6	43.6	43.2	43.2	44.3	44.3	44.7	43.4	45.6	41.3
08:45	43.1	43.9	43.6	43.5	44.6	44.5	45.2	43.8	45.9	40.8
09:15	43.3	43.5	43.4	43.5	44.7	44.6	45.2	43.5	46.2	40.6
09:45	43.2	43.8	43.7	43.6	44.8	44.7	45.1	43.8	46.2	40.7
10:15	43.4	43.7	43.6	43.5	44.8	44.7	45.4	43.7	46.3	40.7
10:45	43.3	43.8	43.7	43.5	44.9	44.8	45.3	43.8	46.4	41
11:15	43.3	43.8	43.7	43.7	44.9	44.7	45.2	43.8	46.3	40.9
11:45	43.5	44	43.8	43.9	44.9	44.7	45.5	44.1	46.3	40.7
12:15	43.5	43.8	43.6	43.7	44.6	44.5	45.5	43.9	46.3	40.4
12:45	43.6	43.8	43.7	43.9	44.9	44.7	45.5	43.9	46.3	40.4
13:15	43.6	43.9	43.8	43.9	44.8	44.6	45.6	43.9	46.4	40.8
14:15	43.6	43.8	43.7	43.9	44.8	44.7	45.5	43.9	46.3	40.6
14:45	43.5	44.1	44	43.9	45	44.9	45.5	44.2	46.4	40.7
15:15	43.6	43.9	43.7	43.8	44.7	44.5	45.5	43.9	46.4	40.4
15:45	43.8	43.9	43.8	44.1	44.9	44.8	45.5	44	46.3	40.4

COMMENTS - TEST No. 2

1.) THERM#1 AMBIENT (CH#39)
2.) THERM#2 TOP TRAY
3.) THERM#3 BOTTOM TRAY
4.) THERM#4 AIR SPACE
5.) CURR START A .2 B .2 C .2
6.) VOLT START A .015 B .018 C .026
7.) CURR START A .9 B .9 C .9
8.) VOLT START A .048 B .048 C .055
9.) CURR START A 6.8 B 6.8 C 6.8
10.) VOLT START A .471 B .470 C .550
11.) CURR START A 2.8 B 2.8 C 2.8
12.) VOLT START A .309 B .337 C .306
13.) CURR START A 53.0 B 53.0 C 53.0
14.) VOLT START A 1.507 B 1.378 C .806
15.) CL-542 TEST #2 11/3/83 START 0515
16.) VOLT END A .0109 B .0147 C.0240
17.) CUR END ALL .20AMP
18.) VOLT END A .0488 B .0495 C .0569 CUR
19.) CUR END A .80 B .80 C .80
20.) VOLT END A .495 B .50 C .50
21.) VOLT END A .323 B .353 C .323
22.) CURR END ALL 2.8AMP
23.) VOLT END A 1.572 B 1.462 C .838
24.) CUR END ALL 53.0 AMPS
25.) END TEST 2 CL 542 1600 TIME
26.) CH 9,18,26,27,28,37, ON 2.8 AMP CIRCUIT
27.) CH 5,8 ON 53 AMP CIRCUIT
28.) CH 6,7 ON #12 CABLE, 6.8 AMP CIRCUIT
29.) CH 10,12 ON 4/C CABLE, 6.8 AMP CIRCUIT
30.) CH 17,36 ON .17 AMP CIRCUIT
31.) CH 11,20,25 ON .71 AMP CIRCUIT

[illegible]

TEST No. 2

ESTERLINE ANGUS DATA

TIME	CH#0	CH#2	CH#3	CH#4	CH#5	CH#6	CH#7	CH#8	CH#9	CH#10	CH#11
05:45	29.6	28.7	32.7	21.7	35.1	21.4	21.8	34.3	22.1	23.3	22
06:15	30	33.6	36.8	29	43.6	28.6	29.1	42.8	30	30.4	30
06:45	30.2	36.4	38.4	34.2	49.4	34.5	34.6	49.9	34.9	35.6	34.7
07:15	30.5	38.3	39.8	37.6	53.1	38.2	38.4	52.2	38.3	38.8	37.9
07:45	30.8	39.4	40.8	39.7	55.3	40.5	40.7	54.1	40.2	40.5	39.8
08:15	31	40	41.2	40.9	56.3	41.9	41.9	55.5	41.1	41.6	40.9
08:45	31.2	40.4	41.7	41.8	56.9	42.8	42.8	56	41.8	42.2	41.6
09:15	31.3	40.5	41.4	42.4	57.2	43.4	43.4	56.3	42.4	42.7	42
09:45	31.3	40.5	41.2	42.5	57.6	43.4	43.6	56.5	42.6	43.2	42
10:15	31.5	40.7	41.4	42.9	57.7	43.9	43.9	56.7	42.8	43.2	42.4
10:45	31.5	40.9	41.7	42.9	57.8	43.9	43.8	56.9	42.9	43.4	42.6
11:15	31.4	41	41.9	42.9	57.7	43.9	44.1	56.9	43.1	43.4	42.5
11:45	31.4	41.1	41.9	42.9	58.2	44	44.1	57.2	42.9	43.5	42.6
12:15	31.3	40.8	41.5	43.1	58	44	44.1	56.9	43.1	43.6	42.5
12:45	31.3	40.9	41.6	43.1	58	44.1	44.1	57.1	43	43.4	42.6
13:15	31.3	41.1	42	43	58.1	44	44.1	57	43.1	43.6	42.4
13:45	31.3	41.1	42	43.2	58.1	44.2	44.4	57.1	43.2	43.7	42.6
14:45	31.1	40.8	41.4	43.3	58.1	44.4	44.3	57.1	43.2	43.6	42.7
15:15	31	41.2	42	43.2	58.3	44.1	44.3	57.1	43.2	43.7	42.7

TIME	CH#12	CH#17	CH#18	CH#20	CH#25	CH#26	CH#27	CH#28	CH#36	CH#37	CH#39
05:45	23.2	22	23.5	22.1	21.7	23.3	23.3	22.7	22.1	24.1	35.8
05:15	30.7	29.5	31.5	29.4	29.4	31.5	31.4	30.4	29.6	32.3	39.6
06:45	35.8	34.4	36.4	34.5	34.6	36.7	36.4	35.4	34.6	37.4	39.8
07:15	39	37.6	39.1	37.5	37.6	39.5	39.5	38.8	37.7	40.6	40.3
07:45	40.8	39.3	40.6	39.4	39.3	41.1	41.1	40.5	39.5	42.5	40.6
08:15	41.8	40.2	41.4	40.4	40.4	42.1	42.1	41.5	40.6	43.4	40.7
08:45	42.5	40.9	42	41.2	41.1	42.7	42.7	42.2	41.2	44.1	40.8
09:15	42.8	41.2	42.4	41.6	41.5	43.1	43.1	42.5	41.8	44.4	40.5
09:45	43.2	41.5	42.4	41.7	41.8	43.3	43	42.8	41.9	44.4	40.3
10:15	43.2	41.7	42.7	42	42	43.5	43.4	42.9	42.2	44.7	40.7
10:45	43.5	41.8	42.7	42.1	41.9	43.4	43.5	43.1	42.3	45.1	40.9
11:15	43.5	41.8	42.9	42.2	42.1	43.6	43.4	43.1	42.5	44.8	40.7
11:45	43.7	42.1	42.7	42.1	42.1	43.6	43.5	43.3	42.3	45	40.7
12:15	43.8	42	42.8	42.2	42.2	43.7	43.3	43.3	42.4	44.9	40.5
12:45	43.5	41.9	42.8	42.2	42.2	43.7	43.7	43.2	42.4	44.9	40.7
13:15	43.8	42.1	42.8	42.1	42.4	43.8	43.4	43.3	42.4	44.8	40.5
13:45	43.8	42	42.9	42.3	42.4	43.9	43.5	43.3	42.5	44.8	40.7
14:45	43.6	42	43	42.4	42.4	43.8	43.7	43.3	42.5	45.1	40.7
15:15	43.9	42.1	43	42.3	42.4	43.8	43.5	43.4	42.6	45.1	40.8

[illegible]

1.) CL 542 TEST 3 11/11/83 TIME 0545
2.) CHANNEL 38 AMBIENT
3.) CHANNEL 2 TRAY TOP
4.) CHANNEL 3 TRAY BOTTOM
5.) CHANNEL 4 TRAY AIRSPACE
6.) CHANNELS 10,12,20,32,33,34,35,38 ARE
ON THE INSULATION, NOT THE CONDUCTOR
7.) CURR START A 53.0 B 53.0 C 53.0
VOLT START A .643 B .744 C .697
8.) CURR START A 36.0 B 36.0 C 36.0
VOLT START A 1.5 B 1.45 C 1.6
9.) CURR START A 2.9 B 2.9 C 2.9
VOLT START A .396 B .399 C .425
10.) CURR START A 16.2 B 16.3 C16.1
VOLT START A 1.987 B 2.02 C 1.98
11.) CURR START A 7.0 B 6.9 C 7.0
VOLT START A .62 B .61 C.62
12.) CURR START A .9 B .8 C .8
VOLT START A .16 B .16 C .16
13.) CURR START A 56.0 B 57.3 C 55 5
VOLT START A .64 B .64 C .67
14.) .71 AMP CKT #12 CHAN'S 11,17,25
15.) 2.8 AMP CKT #12 CH'S 9,18,21,26,27,28
29,37
16.) 6.8 AMP CKT 4/C CH'S 10,12
6.8 AMP CKT #12 CH'S 30,31
17.) 16 AMP CKT #6 CH'S 22,24
16 AMP CKT 4/C CH'S 32,33
16 AMP CKT #12 CH'S 36,15
18.) 36.0 AMP CKT #4 CH'S 20,38
36.0 AMP CKT #6 CH'S 34,35
19.) 53.0 AMP CKT #4 CH'S 5,8
20.) 60.0 AMP CKT #2 CH'S 6,7
21.) CURR END A 47.4 B 52.0 C 53.7
22.) VOLT END A .648 B .692 C .712
23.) CURR END A 36.6 B 36.7 C 36.2
24.) VOLT END A 1.529 B 1.465 C 1.607
25.) CURR END A 2.9 B 2.8 C 2.9
26.) VOLT END A .416 B .414 C .441
27.) CURR END A 16.2 B 16.3 C 16.1
28.) VOLT END A 2.40 B 2.04 C 2.26
29.) CURR END A 6.7 B 6.8 C 7.0
30.) VOLT END A .594 B .620 C .627
31.) CURR END A 0.9 B 0.9 C 0.8
32.) VOLT END A .117 B .122 C .115
33.) CURR END A 55.6 B 51.8 C 55.9
34.) VOLT END A .638 B .585 C .697
35.) END OF TEST #3 CL-542 11/11/83 1425

TEST NO. 3

ESTERLINE ANGUS DATA

TIME	CH#0	CH#2	CH#3	CH#4	CH#5	CH#6	CH#7	CH#8	CH#9	CH#10	CH#11
05:45	29.4	22.8	23.4	24.2	24.3	24.4	24.8	24.5	24.3	24.5	24.3
06:15	29.5	31.5	34.1	27.5	40.4	35.4	35.7	40.6	30.1	29.7	29
06:45	29.5	36.6	39.7	35.5	50.9	45.2	45.5	51.5	38.8	37.7	37.1
07:15	29	39.2	41.4	42.4	57	52	52.1	58.1	44.8	44	43.3
07:45	28.9	41.1	42.7	47.7	61.4	56.6	56.7	62.2	49.2	48.5	47.5
08:15	29.1	42.6	43.8	51.2	63.8	59.4	59.4	64.8	51.8	50.9	50.2
08:45	29.5	43.6	44.7	52.9	65.5	60.9	60.9	66.3	53.5	52.7	51.8
09:15	29.9	43.7	44.5	54.2	66.7	62.1	62.1	67.6	54.5	53.5	52.6
09:45	30.2	44.2	45	55	67.6	63	62.8	68.4	55	53.7	53.3
10:15	30.4	44.3	44.8	55.4	67.9	63.4	63.4	68.8	55.4	54	53.7
10:45	30.7	44.4	44.9	55.5	68.4	63.7	63.6	69	55.5	54.3	53.8
11:15	30.7	44.6	45.3	55.8	67.9	63.4	63.4	68.7	55.7	54.4	53.8
11:45	30.8	44.6	45.2	55.6	67.6	63.1	63.1	68.3	55.6	54.5	53.9
12:15	30.8	44.5	45.1	55.7	67.5	63	63.1	68.4	55.6	54.5	53.9
12:45	30.8	44.8	45.6	55.7	67.6	63.3	63.3	68.4	55.6	54.5	54
13:15	30.6	44.3	44.8	55.7	67.1	62.9	63.1	68.2	55.6	54.5	53.7
13:45	.30.4	44.6	45.1	55.8	67	62.8	63	68.1	55.6	54.5	53.8

TIME	CH#12	CH#15	CH#17	CH#18	CH#20	CH#21	CH#22	CH#24	CH#25	CH#26	CH#27
05:45	24.4	24.5	24.3	24.5	24.5	24.4	24.3	24.4	24.3	24.4	24.3
06:15	29.8	36.7	28.3	29.3	32.9	31.1	31.8	31.7	30.2	29.4	29.2
06:45	38	45.4	35.9	38.7	41	40.5	41.4	41.2	38.3	38.7	38.7
07:15	44.3	51.8	41.4	45.2	46.9	46.8	48	47.7	44.4	45.5	45.5
07:45	48.9	56	45.3	49.7	51.2	51.3	52.1	51.8	48.4	49.8	49.7
08:15	51.3	58.4	47.6	52.3	53.5	53.9	54.1	53.6	51	52.5	52.3
08:45	53.3	60	49.2	53.7	55	55.5	55.9	55.1	52.7	54	54.1
09:15	54	60.8	49.7	54.6	55.6	56.3	56.4	55.6	53.3	55.1	54.7
09:45	54.4	60.2	50.8	55.2	56.9	57.2	56.3	55.8	53.9	55.5	55.5
10:15	54.6	60.5	50.9	55.5	57.2	57.3	56.5	55.8	54	55.8	55.5
10:45	55	61	51	55.6	57.3	57.6	56.7	56.2	54.5	55	56
11:15	55.2	61.1	51.2	55.5	57.4	57.7	56.9	56.3	54.6	55	56
11:45	55	61	51.2	55.6	57.5	57.4	56.8	56.2	54.5	56.1	55.8
12:15	55.1	60.9	51.3	55.6	57.5	57.4	57	56.1	54.6	55.1	55.8
12:45	55.2	61.2	51.2	55.6	57.5	57.5	56.9	56.3	54.5	56	55.9
13:15	55.1	60.8	51.2	55.4	57.3	57.4	56.7	56.2	54.5	55.9	55.8
13:45	55.2	60.8	51.3	55.4	57.4	57.3	56.7	56.2	54.5	55.8	55.7

TEST No. 3

TIME	CH#28	CH#29	CH#30	CH#31	CH#32	CH#33	CH#34	CH#35	CH#36	CH#37	CH#38
05:45	24.4	24.5	24.5	24.4	24	24.3	24.2	24.2	24.6	24.5	24.8
06:15	29.7	29.6	32.9	32.1	35	37.1	38.5	38.6	41.2	31.6	32.9
06:45	39	39.1	42.5	41.4	45.8	47.3	48.5	48.9	51.8	41.2	41
07:15	45.9	46	49.2	47.7	51.9	54.1	55.2	55.5	58.1	47.8	47.1
07:45	50.4	50.5	53.9	51.6	55.5	58.1	59.2	59.5	62.4	51.9	51
08:15	53.7	53.2	56.7	53.9	57.4	60.4	61.1	61.6	64.9	54.3	53.6
08:45	55.1	54.8	58.4	55	58.6	61.6	62.4	63.2	66.5	56.1	55.3
09:15	56.1	55.7	59.2	55.8	59.1	62.7	62.9	63.6	67.5	56.8	55.8
09:45	56.7	56.1	59.7	55.6	58	61.5	64.2	65.3	66.7	57.5	57.2
10:15	56.9	56.5	60.1	55.6	58	61.9	64.5	65.3	67	57.6	57.4
10:45	57.2	56.7	60.4	56	58.2	62	64.8	65.7	67.3	58.1	57.8
11:15	57.2	56.7	60.3	56.1	58.5	62.1	64.9	65.9	67.2	58.1	57.9
11:45	57.1	56.8	60.3	56	58.3	62.1	64.8	65.6	67.1	57.9	57.9
12:15	57.2	56.8	60.3	55.9	58.4	62.2	64.7	65.7	67.3	57.8	58
12:45	57	56.7	60.3	56.1	58.4	62.2	64.9	65.7	67.1	57.9	57.8
13:15	57	56.6	60.2	56.1	58.2	62	64.7	65.6	66.9	57.8	57.8
13:45	57	56.5	60.1	56.2	58.4	62	64.8	65.7	65.7	57.7	57.8

TIME	CH#39
05:45	23.5
06:15	36.6
06:45	40.3
07:15	40.4
07:45	40.5
08:15	40.7
08:45	40.7
09:15	40.7
09:45	40.7
10:15	40.7
10:45	40.8
11:15	40.8
11:45	40.9
12:15	41.1
12:45	41
13:15	40.9
13:45	41

TEST NO. 4

ESTERLINE ANGUS DATA

TIME	CH#0	CH#1	CH#2	CH#3	CH#4	CH#5	CH#6	CH#7	CH#8	CH#9
08:00	22.1	36.6	35.2	39.4	28.2	27.5	30.1	26.8	27.2	23.4
08:30	23.8	38.3	37.1	38.4	35.4	35	35.4	35.3	34.7	38.3
09:00	25.3	36.3	36.8	37.8	37.1	37	37.1	35.3	36.9	35.6
09:30	26.6	39.1	38.8	39.7	37.9	38	37.9	37.4	37.8	36.4
10:00	27.6	39.5	39.3	40.1	39.4	39.5	39.7	39.1	39.1	35.7
10:30	28.6	39.8	39.9	40.5	40.2	40.3	40.4	40.1	40.2	36.5
11:00	29.2	39.9	39.9	40.6	40.4	40.8	40.5	40.2	40.5	37.8
11:30	29.6	39.8	40.2	41.1	40.6	40.7	40.5	40.1	40.6	62.8
12:00	30	40	40.5	41.5	40.4	41	40.7	40.5	40.6	
12:30	30.3	40	40.7	41.9	40.8	41	41.2	40.1	40.8	40.5
13:00	30.4	40.1	40	40.5	40.8	41	42.9	40	40.9	38.4
13:30	30.6	40.1	40.3	41	41	41.1	40.9	41.7	40.9	39.1
14:00	30.7	40.2	40.8	41.7	40.8	40.9	41.1	40.2	41.1	38.7
14:30	30.7	39.8	40.3	41.7	40.5	41.1	40.9	40.6	40.8	35.7

COMMENTS

1.) TEST 4
2.) VOLT START A 119.5 B 119.4 C 121.8
3.) CURR START A 2.0 B 2.0 C 2.0
4.) CHAN 9 INVALID CL 542 TEST 4
5.) CURR FINISH A 2.0 B 2.0 C 2.0

[illegible]

TEST NO. 5

ESTERLINE ANGUS DATA

TIME	CH#0	CH#1	CH#2	CH#3	CH#4	CH#6	CH#7	CH#9	CH#10	CH#11	CH#12
07:54	19.2	36.7	32.3	35.6	27.7	30.1	32.3	29.8	30.2	31.7	29.3
08:15	20.2	39.1	34.7	37.1	32.5	35.5	38.6	35.2	35.7	37.4	34.6
08:45	21.9	39.7	37	38.7	38.5	42.2	45.9	41.8	42.6	44.5	41.5
09:15	23.4	39.6	38.4	39.7	42.9	47.4	51.1	46.7	48.1	50	46.8
09:45	24.8	39.7	39.3	40.4	46.2	50.7	55.2	50.6	52.2	54.2	50.8
10:15	25.8	40.1	40.2	40.8	48.4	53.5	58.1	53.5	54.8	56.9	53.5
10:45	26.8	40	41	41.5	50.4	55.3	59.9	55.3	57	58.7	55.4
11:15	27.8	40	41.3	42	51.8	56.5	61.9	56.4	58.2	50.4	56.8
11:45	28.6	39.9	41.5	42.4	52.7	57.8	63.1	57.4	59.2	60.9	57.8
12:15	29.2	40	41.8	42.5	53.3	58.6	63.3	58.3	60.2	62	58.5
12:45	29.6	39.8	41.7	41.9	53.7	59.1	63.8	58.6	60.5	62	58.9
13:15	29.8	39.8	41.4	41.7	53.9	59.2	64.5	58.8	60.9	62.8	59.4
13:45	30.1	39.7	41.7	42	53.9	59.5	64.3	58.9	60.9	62.4	59.5
14:15	30.4	39.9	42	42.5	54	59.7	64.4	58.9	60.9	62.4	59.6
14:45	30.7	39.9	42.2	42.7	54.4	59.9	64.8	59.1	61.2	62.7	59.6
15:15	30.9	39.6	41.6	41.9	54.3	60	64.8	59.3	61.2	62.8	59.7
15:45	31.1	40	42	42.1	54.5	60.3	65	59.5	61.5	63.3	59.9

COMMENTS

1.) TEST 5 CL-542 10/20/83 0730
2.) VOLT START A .589 B .844 C .611
3.) CURR START A 72.0 B 72.0 C 72.0
4.) CHNL 12 ON OUTSIDE INSULATION
5.) 1-AMBIENT 2-TOP CONDUIT
6.) 3-BOTTOM CONDUIT 4-AIR SPACE
7.) VOLT FINISH A .631 B :997 C :657
8.) CURR FINISH A 72.0 B 72.1 C 71.9
9.) END TEST 5 CL 542 10/20/83 1545

COMMENTS - TEST NO. 6

1.) CL-542 TEST 6 2ND RUN 11/18 0515
2.) CHANNEL 39 AMBIENT
3.) CHANNEL 2 TRAY TOP
4.) CHANNEL 3 TRAY BOTTOM
5.) CHANNEL 4 AIR SPACE
6.) 20 AMP CKT CHANNELS 9,12
7.) 25 AMP CKT CHANNELS 8,10
8.) 40 AMP CKT CHANNELS 5,7
9.) 50 AMP CKT CHANNELS 16,20,36
10.) CURR START A 20.3 B 20.4 C 20.3
11.) VOLT START A .746 B .769 C .786
12.) CURR START A 25.4 B 25.0 C 25.1
13.) VOLT START A 1.260 B 1.256 C 1.597
14.) CURR START A 40.3 B 40.0 C 40.3
15.) VOLT START A .226 B .214 C .245
16.) CURR START A 50.0 B 50.0 C 50.0
17.) VOLT START A .204 B .209 C .257
18.) END TEST 6 2ND 11/18/83 TIME 1545
19.) CURR END A 20.5 B 21.5 C 21.1
VOLT END A .785 B.836 C .837
20.) CURR END A 25.4 B 25.3 C 25.2
VOLT END A 1.315 B 1.397 C 1.265
21.) CURR END A 41.1 B 40.4 C 40.9
VOLT END A .240 B .225 C.256
22.) CURR END A 50.8 B 49.8 C50.4
VOLT END A .227 B.211 C.278

TEST No. 6

ESTERLINE ANGUS DATA

TIME	CH#2	CH#3	CH#4	CH#5	CH#7	CH#8	CH#9	CH#10	CH#12	CH#16	CH#20
05:15	21.5	23.9	25	25.2	25.3	24.9	25.3	25.6	25.5	25.3	25.6
05:45	37.7	35	25.7	26.8	27.1	26.5	27.3	27.1	27.4	26.7	26.7
06:15	39.7	38	28.8	29.9	30.1	29.8	30.3	29.7	30.2	29.6	29.6
06:45	39.8	38.8	32.3	32.5	32.9	33.1	33	32.7	33.3	32.8	32.6
07:15	40.2	39.6	34.5	35.3	35.8	35.8	36	35.1	35.7	35.7	35.4
07:45	40.6	40.1	36.5	37.4	37.8	37.9	37.8	37.4	37.9	37.7	37.3
08:15	40.7	40.4	38.1	39.2	39.7	39.4	39.6	39.1	39.4	39.2	39.4
08:45	39.4	40.2	39.4	40.6	41	41.1	40.9	40.7	41	40.4	40.5
09:15	39.3	40.7	40.2	41.9	42.2	41.8	42.3	41.6	41.8	41.5	41.5
09:45	40.1	41.3	41.1	42.8	43.1	42.4	43	42.4	42.5	42.1	42.3
10:15	40.9	41.5	41.8	43.3	43.4	43.2	43.4	43.3	43.4	42.5	42.7
10:45	40.2	41.2	42.2	43.6	43.8	43.4	44	43.7	43.7	42.9	43.2
11:15	39.2	41.1	42.4	44.1	44.1	43.5	44.4	43.9	44.2	43.1	43.5
11:45	40.1	41.6	42.7	44.6	44.6	43.8	44.8	44.3	44.5	43.5	43.8
12:15	40.9	41.8	43.1	44.8	44.8	44.1	45.1	44.6	44.8	43.5	44
12:45	40.3	41.6	43.2	45.2	45.1	44.2	45.2	44.6	44.9	43.9	44.2
13:15	39.4	41.2	43.3	44.9	44.9	44.4	45.2	45	45.1	43.8	44.2
13:45	40	41.5	43.4	45.3	45.1	44.5	45.5	45	45.2	43.9	44.3
14:45	39.1	41.3	43.6	45.4	45.2	44.6	45.4	45.3	45.5	44.1	44.4
15:15	40.1	41.6	43.5	45.4	45	44.6	45.6	45.4	45.5	44.1	44.4
15:45	39.7	41.5	43.5	45.5	45.3	44.6	45.6	45.2	45.5	44.3	44.5

TIME	CH#36	CH#39
05:15	25.5	24.5
05:45	26.7	36.7
06:15	29.8	39.5
06:45	32.7	39.9
07:15	35.4	40.2
07:45	37.3	40.3
08:15	39.3	40.2
08:45	40.5	40.2
09:15	41.4	40.5
09:45	42.1	40.6
10:15	42.7	40.7
10:45	43.2	40.1
11:15	43.4	40.2
11:45	43.7	40.5
12:15	43.9	40.5
12:45	44	40.5
13:15	44.2	40.4
13:45	44.3	40.5
14:45	44.4	40.4
15:15	44.4	40.7
15:45	44.2	40.5

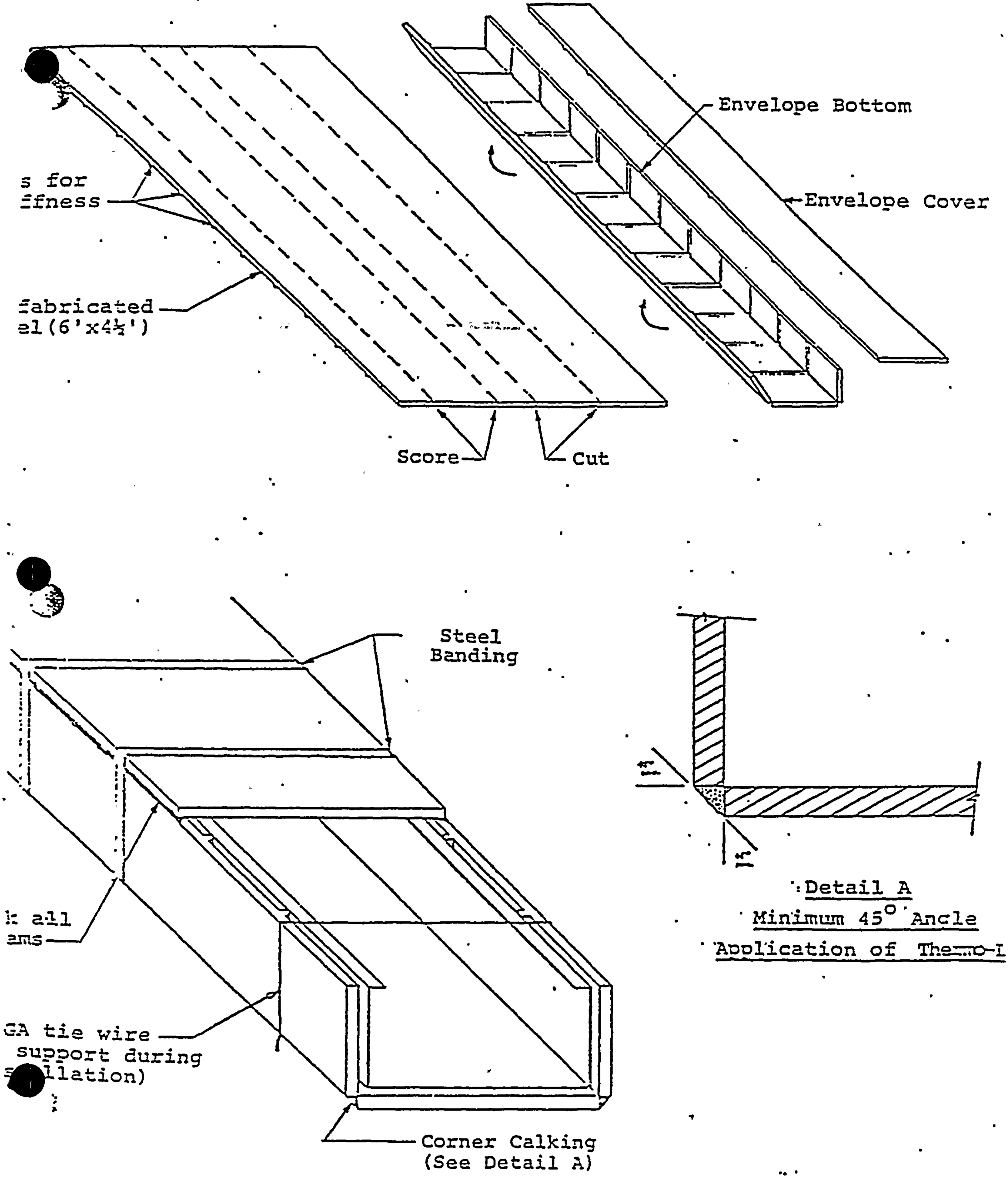


FIGURE 1

Typical Cable Tray Envelope Assembly

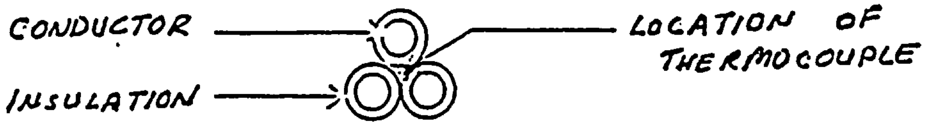


FIGURE 2

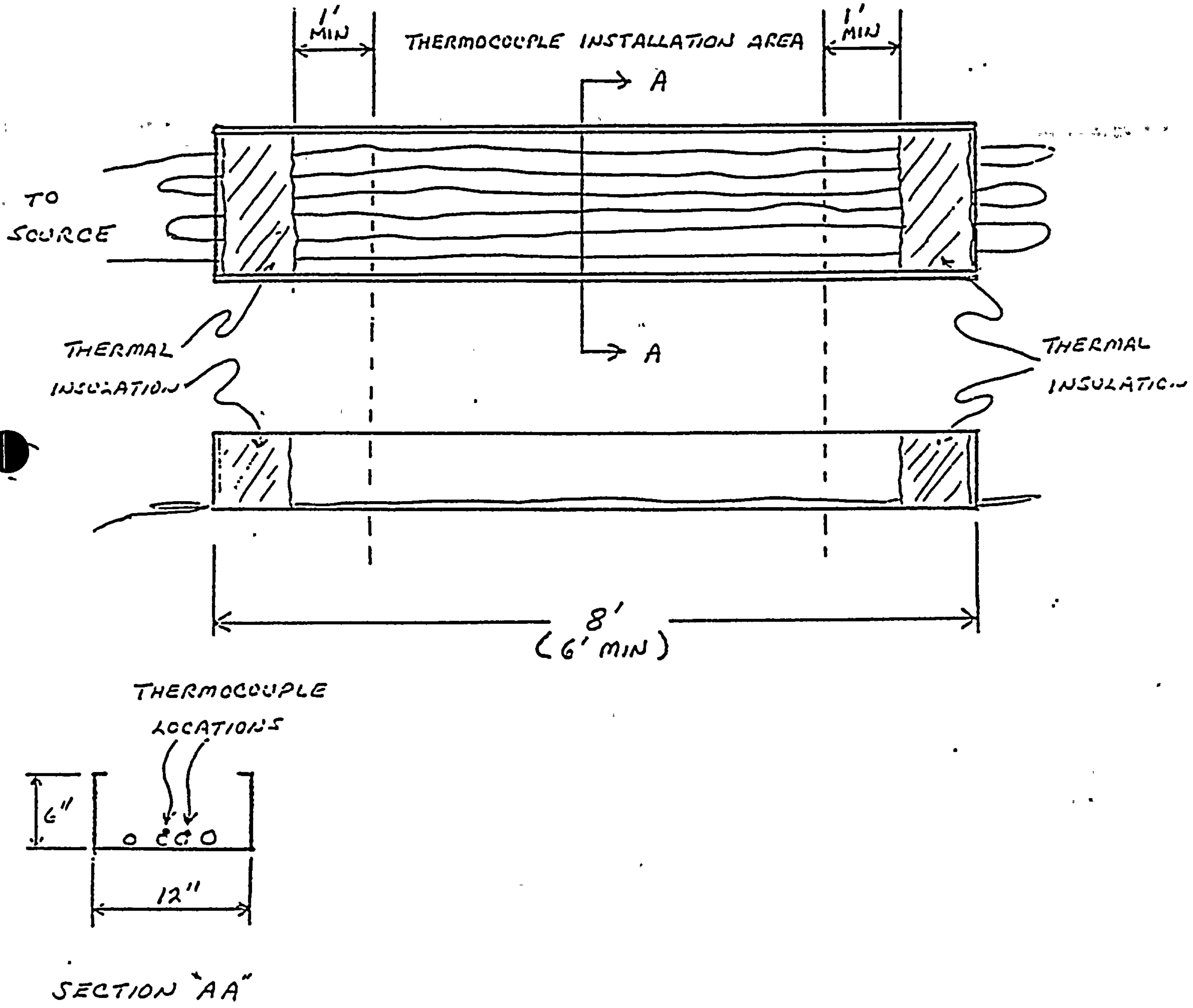
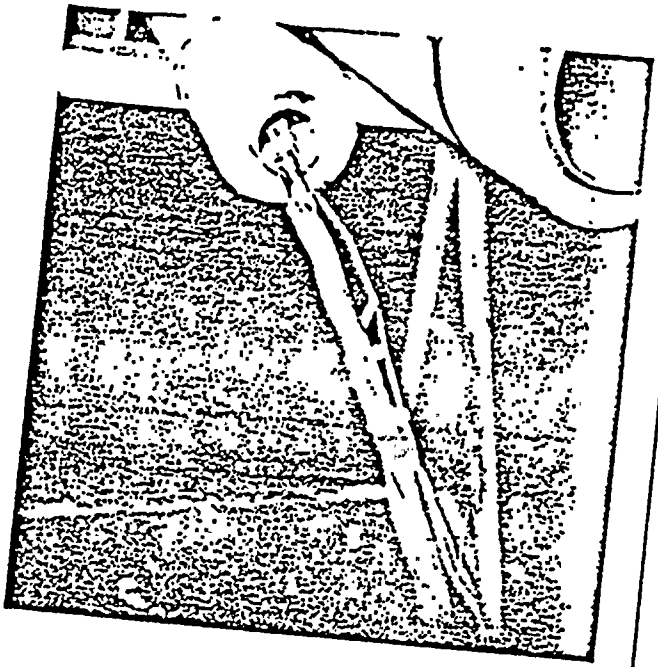
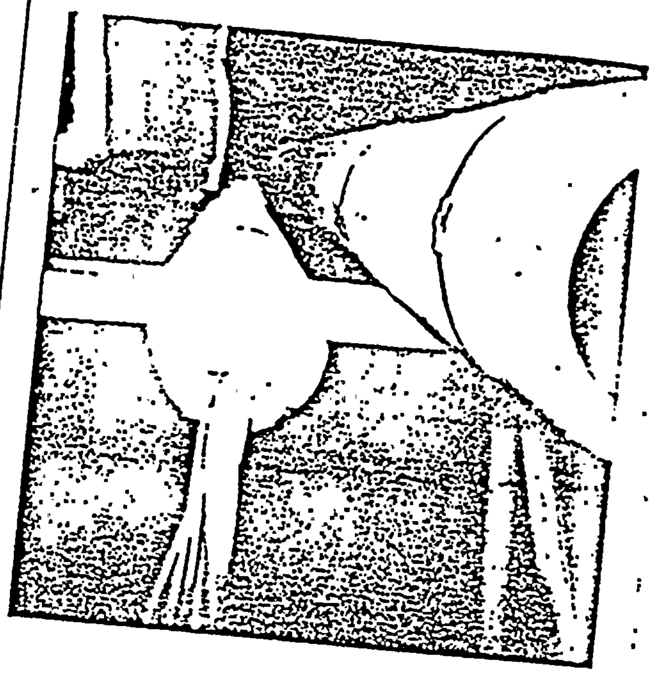


FIGURE 3



TEST #4



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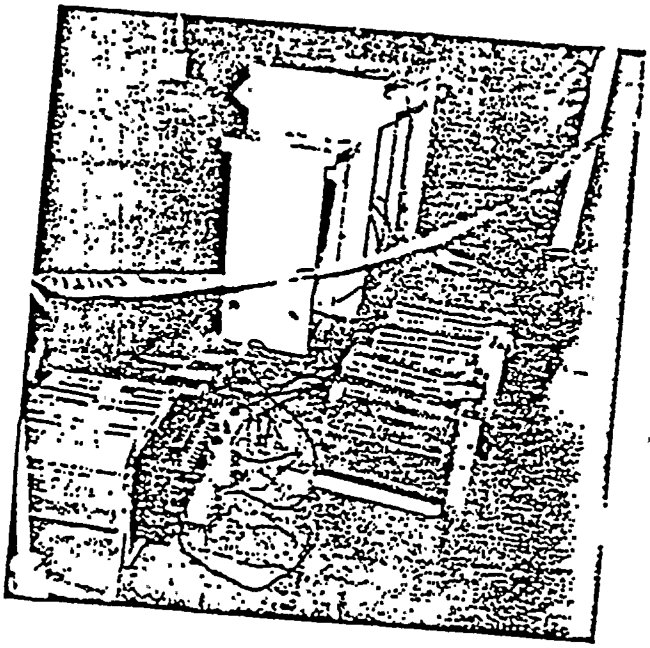
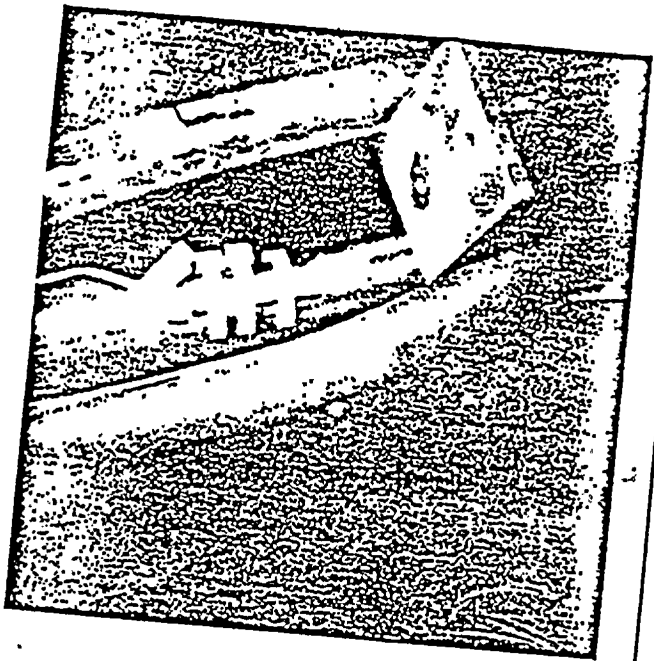
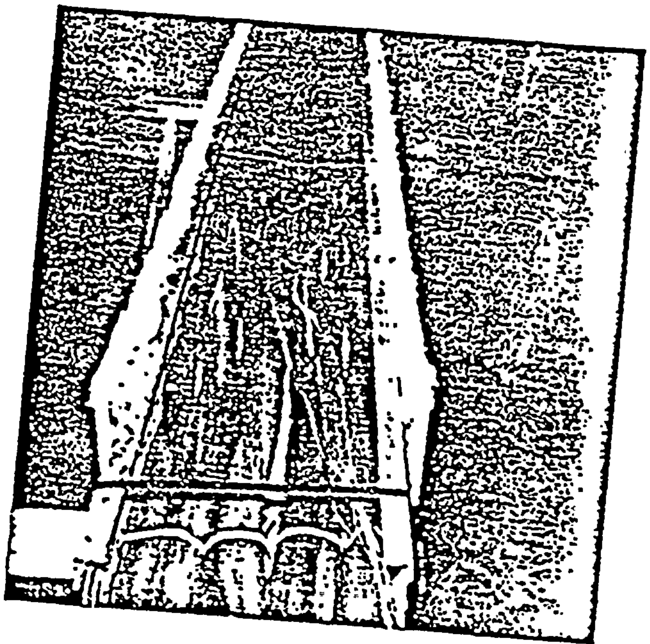


TEST #4
POWER SOURCES



TEST #5

TEST #5
POWER SOURCES



TEST #6