NRL REPORT 3936

CURRENT AND TEMPERATURE RISE IN AIRCRAFT CABLES

PART II

UNIFORM BUNDLES UNDER STEADY-STATE CONDITIONS

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March 7, 1952

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ABSTRACT

The steady-state relations between current and temperature rise for single cables in air were described in NRL Report No. 3587 as a first step toward the solution of the bundle-rating problem.

As the second step an empirical study of the continuous current capacity of aircraft cables in uniform bundles (bundles composed of cables of a single size) was undertaken. The investigation of the effects on current capacity of (1) the number of cables loaded simultaneously, (2) the position of the loaded cables in the bundle, (3) the total number of cables in the bundle, and (4) the spacing between adjacent cables, shows that a set of minimum conditions can be defined to serve as a basis for rating cables in uniform bundles. The study shows that an approximate analysis of the heat flow in the bundle is possible. Application of this analysis to the calculation of currents for cables in uniform bundles results in values which differ by less than five percent from measured currents.

PROBLEM STATUS

This report is an interim report on NRL Problem E01-08 and concludes the work on the steady-state relations between current and temperature rise for cables in uniform bundles. An investigation of the relations between current and temperature rise in mixed bundles is now in progress.

AUTHORIZATION

NRL Problem No. E01-08
RDB Project NR 421-080
BuAer letter to NRL, Aer-E-312-JWA, F 36-1(1)
Serial No. 313857 dated December 20, 1945

Manuscript submitted January 8, 1952

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INTRODUCTION

The need for bundle ratings arises from the fact that cables installed in aircraft are grouped together for a portion of the cable run from the distribution bus to the individual load devices. Stated in its simplest form, the bundle-rating problem is to determine a method for selecting the proper combination of cable sizes for any given group of currents, or–stated conversely–given a group of cables, to find the combination of currents which may be carried safely by the group.

There are two general criteria by which the current capacity of a cable is limited: (1) the maximum voltage drop in the conductor and (2) the maximum insulation temperature. This paper will be concerned with the latter only. The fact that the temperatures of the insulation and the conductor approach each other at their common boundary makes it possible to state the thermal limitation on current capacity as a maximum conductor temperature. When applied to a cable bundle, this criterion requires that the hottest conductor must not exceed some predetermined temperature.

The factors which determine the temperature of the hottest conductor are the number and properties of the component cables, the number of cables loaded simultaneously, the position of the loaded cables in the bundle, the over-all size and shape of the bundle, the spacing between adjacent cables, and the bundle environment.

The general solution of the bundle-rating problem is not immediately attainable for four reasons. First, there is a lack of information concerning the numerous factors. Second, it is difficult to express quantitatively such parameters as bundle shape and spacing between adjacent cables. Third, the criterion that the hottest conductor in a bundle must not exceed some specified temperature permits many solutions for the problem, that is, by decreasing the current in some cables and increasing it in others, one obtains alternative current values which satisfy the criterion. Finally, the complex bundle geometry gives rise to elaborate boundary conditions for conduction, convection, and radiation.

Simplification of Problem

Recognition of the difficulties of the bundle-rating problem in its most general form made it evident that an investigation of the problem under much more restricted conditions than those which prevail in practice should be undertaken. In particular, it was believed that an empirical study of uniform bundles (bundles composed of cables of a single size) would be a useful step. The study was conducted under the following simplifying conditions:

1. Cables were bound at intervals not exceeding 24 inches so as to form a cylindrical-shaped bundle.

2. The relative positions of the component cables were maintained throughout the bundle length.

3. Bundles were suspended horizontally in still air. For convenience, the ambient air was fixed at room temperature (25°C) and sea-level pressure.

4. Each loaded cable carried the same current.

Definition of Current Rating

For convenience, current rating is defined as the continuous current per loaded cable which produces a 40°C rise in the temperature of the hottest conductor of the bundle. The terms "current capacity," "current per cable," and "current value" will be used synonymously with "current rating" as defined here. The selection of 40°C as the maximum temperature rise is arbitrary. Where values other than 40°C are discussed, they will be indicated specifically.

Factors Affecting Current Rating

With the restrictions mentioned, current rating becomes a function of the dimensions, resistance, and thermal properties of the component cables, the total number of cables in the bundle, the number of cables loaded simultaneously, the position of the loaded cables in the bundle, and the spacing between adjacent cables.

EXPERIMENTAL PROCEDURE

The test program was initiated with a bundle of 19 AN-18 cables bound tightly at one-inch intervals in a manner to minimize the distance between adjacent cables (bundles tied in such a manner are called "tight" bundles). A diagram of the cross-section of such a bundle of 19 cables is shown in Figure 1. A series of tests was performed to determine current rating as a function of the position of the loaded cables and of the number of cables loaded simultaneously. Only those positions in which the loaded cables were situated symmetrically about the bundle center and those which gave either the best or the poorest current rating were chosen.

To determine the effect of the total number of cables in the bundle on current rating, tests similar to those made on the initial bundle were performed on tight bundles of 3, 7, and 37 AN-18 cables. In addition, the current rating was obtained for a single AN-18 cable in air.

To ascertain the effect of the spacing between adjacent cables on current rating, tests similar to those conducted on tight bundles were performed on a bundle of 37 AN-18 cables tied at 6-, 12-, and 24-inch intervals. (Bundles tied at 6-, 12-, or 24-inch intervals are denoted "loose" bundles.)

The whole series of tests was repeated on bundles of 3, 7, and 19 cables of size AN-8 and of size AN-1/0 in order to determine the effect of the size of the constituent cables on current rating. In addition, current ratings for a single cable in air were obtained for these sizes.

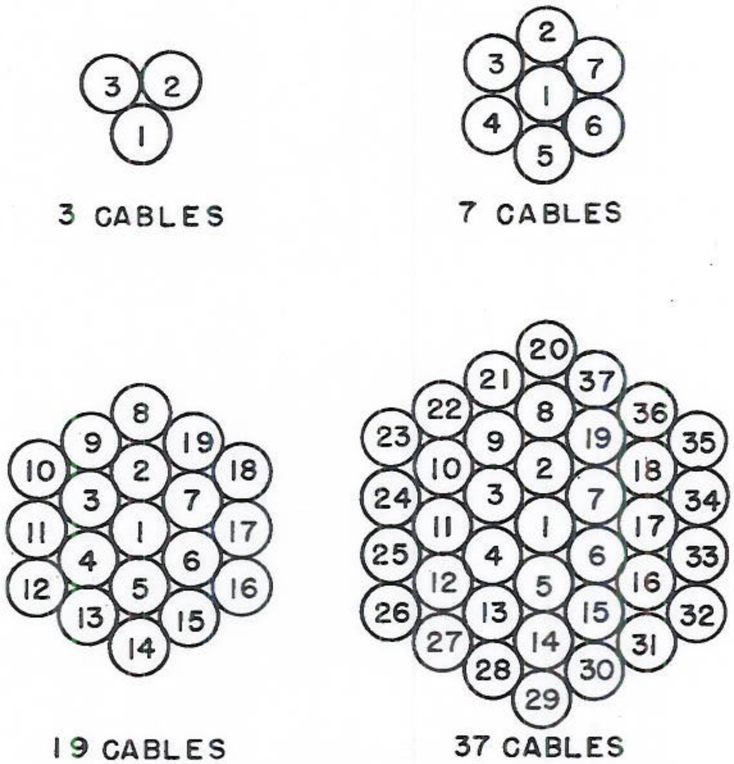

Figure 1 - Cross-sections of tight bundles of 3, 7, 19, and 37 cables showing the cable position numbers

A complete list of the bundles studied is given in Table 1; bundles will be referred to by the designations given there. The numbers which make up the designation are the total number of cables in the bundle, the individual cable size, and the interval between ties, in that order. Diagrams of the tight bundles are shown in Figure 1; the numbers which appear on the diagram are given so that cable positions may be located. The manner of binding tight and loose bundles is illustrated in Figure 2 for the case of 19 AN-8 cables. In tying the tight bundles, lacing of one-inch interval was used in all cases except for bundle 19-1/0-3, where lacing of three-inch interval was deemed sufficient to produce a tight bundle. A description of the methods employed and the conditions under which measurements were obtained is given in Appendix I.

EMPIRICAL RESULTS (Tight Bundles)

In the following description of the empirical results, each factor affecting current rating is considered in turn. When the effect of one factor is being discussed, it may be assumed that those remaining are held constant except where specifically indicated. Emphasis is placed on the conditions for which minimum current ratings are obtained.

Number of Cables Loaded

If every possible combination of cables in a given bundle were loaded in turn and the current per cable for each test were plotted as a function of the number of cables loaded, it would be found that current rating is not a single-valued function. This result is illustrated for a tight bundle of 37 AN-18 cables in Figure 3. Points which lie on the upper and lower curves correspond to the best and poorest heat transfer conditions, respectively. The spread of current values is due to the variety of positions which can be occupied by a given number of loaded cables. Additional information concerning the effect of the number of cables loaded is presented as the other factors are introduced.

Position of the Loaded Cables

The term position may be used in two senses. First, it may refer to the configuration of the loaded cables, that is, the pattern of and distances between the current-carrying cables. Second, it may mean the location of a given configuration of loaded cables with respect to the bundle center.

TABLE 1
List of Bundles Studied

Bundle Designation	No. of Cables in Bundle	AN Size of Constituent Cables	Distance between Ties in Inches
3-18-1	3	18	1
7-18-1	7	18	1
19-18-1	19	18	1
37-18-1	37	18	1
37-18-6	37	18	6
37-18-12	37	18	12
37-18-24	37	18	24
3-8-1	3	8	1
7-8-1	7	8	1
19-8-1	19	8	1
19-8-6	19	8	6
19-8-12	19	8	12
19-8-24	19	8	24
3-1/0-1	3	1/0	1
7-1/0-1	7	1/0	1
19-1/0-3	19	1/0	3
19-1/0-6	19	1/0	6
19-1/0-24	19	1/0	24

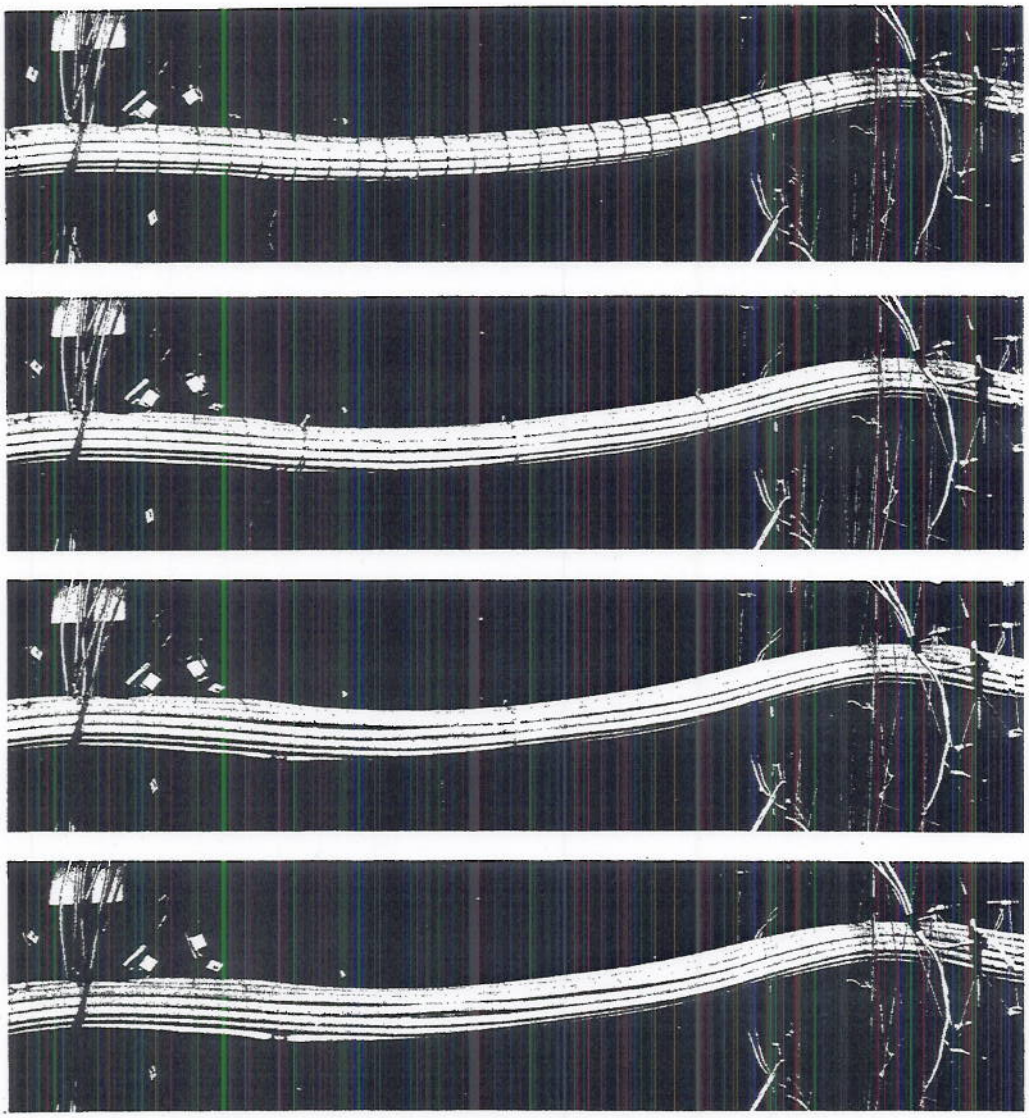

Figure 2 - Bundles of 19 AN-8 cables bound by 1-inch lacing and by 6-, 12-, and 24-inch ties

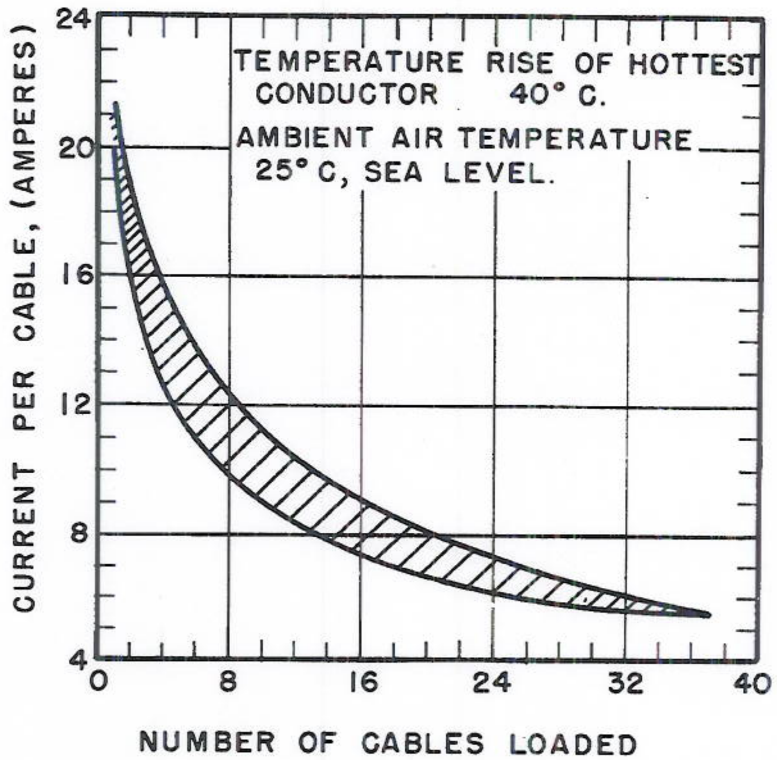

Figure 3 - Effect of the number of cables loaded on current rating for a tight bundle of 37 AN-18 cables

Configuration of the Loaded Cables — The current capacity increases as the distance between loaded cables is increased. Current capacity is a minimum when the loaded cables occupy adjacent positions in the bundle and form a compact group. The ratio of current ratings for the two configurations which give maximum and minimum values for the same number of cables loaded simultaneously can be as high as 1.3. A summary of the configuration effect is given in Table 2.

Location of a Given Configuration of Loaded Cables with Respect to the Bundle Center — The location for which a given configuration has a minimum current rating varies with the number of cables loaded and the total number of cables in the bundle. If the current capacity of the centermost position is taken as a reference, it is found that the current values for alternative locations differ by less than seven percent in each of the tight bundles. The effect of location of the loaded cables on current rating is summarized in Table 3.

Total Number of Cables in the Bundle

Over the range observed, current rating for a given number of cables loaded increases as the total number of cables increases. In particular, current capacity is a minimum when the total number of cables in the bundle is equal to the number of cables loaded. Thus, three cables in a bundle of three carry less current per cable than three cables in a bundle of 7, 19, or 37. In the bundles of 7, 19, or 37 there are several possible locations for the three loaded cables. The current capacity for all the alternative cases exceeds the value for three cables in a bundle of three. The experimental results are shown in Figure 4.

TABLE 2
Effect of Configuration of Loaded Cables
on Current Rating of Tight Bundles

Bundle Designation	Position Numbers of Loaded Cables	Current Rating in Amperes
Three Cables Loaded:		
19-18-1	2, 8, 9	13.8
	8, 9, 19	14.0
	8, 12, 16	16.3
37-18-1	8, 20, 37	14.3
	20, 26, 32	16.6
Six Cables Loaded:		
19-18-1	1-3, 8-10	10.8
	2-7	11.2
	9, 11, 13, 15, 17, 19	12.5
37-18-1	1-3, 8-10	10.8
	20, 23, 26, 29, 32, 35	13.9
19-8-1	1-3, 8-10	44.5
	2-7	46.0
19-1/0-3	1-3, 8-10	149
	2-7	152
Twelve Cables Loaded:		
19-18-1	1-3, 5, 7-11, 17-19	8.2
	8-19	9.1
37-18-1	1-3, 7-10, 19-22, 37	8.4
	8-19	9.1
	9, 11, 13, 15, 17, 19, 20, 23, 26, 29, 32, 35	9.7
	2, 4, 6, and 21, 23, 25, 27, 29, 31, 33, 35, 37	9.7
	20, 22, 23, 25, 26, 28, 29, 31, 32, 34, 35, 37	10.4
19-8-1	1-3, 5, 7-11, 17-19	35.5
	8-19	39.5
19-1/0-3	1-3, 5, 7-11, 17-19	118
	8-19	138

TABLE 3
Effect of Location of a Given Configuration of Loaded Cables on Current Rating of Tight Bundles

Bundle Designation	Position Numbers of Loaded Cables	Current Rating in Amperes
One Cable Loaded:		
7-18-1	1	20.1
	2	19.6
19-18-1	1	21.0
	2	20.6
	8	20.0
37-18-1	1	21.2
	20	20.1
7-8-1	1	83.3
	2	79.7
19-8-1	1	84.0
	8	80.0
7-1/0-1	1	271
	2	264
	5	257
19-1/0-3	1	272
	8	262
	14	259
Three Cables Loaded:		
19-18-1	1, 2, 3	14.1
	2, 8, 9	13.8
37-18-1	1, 2, 3	13.9
	2, 8, 9	13.9
	8, 20, 37	14.3
19-8-1	1, 2, 3	58.0
	2, 8, 9	56.5
19-1/0-3	1, 2, 3	189
	2, 8, 9	189
	5, 13, 14	189
Six Cables Loaded:		
37-18-1	2, 8, 9, 20-22	11.3
	1-3, 8-10	10.8

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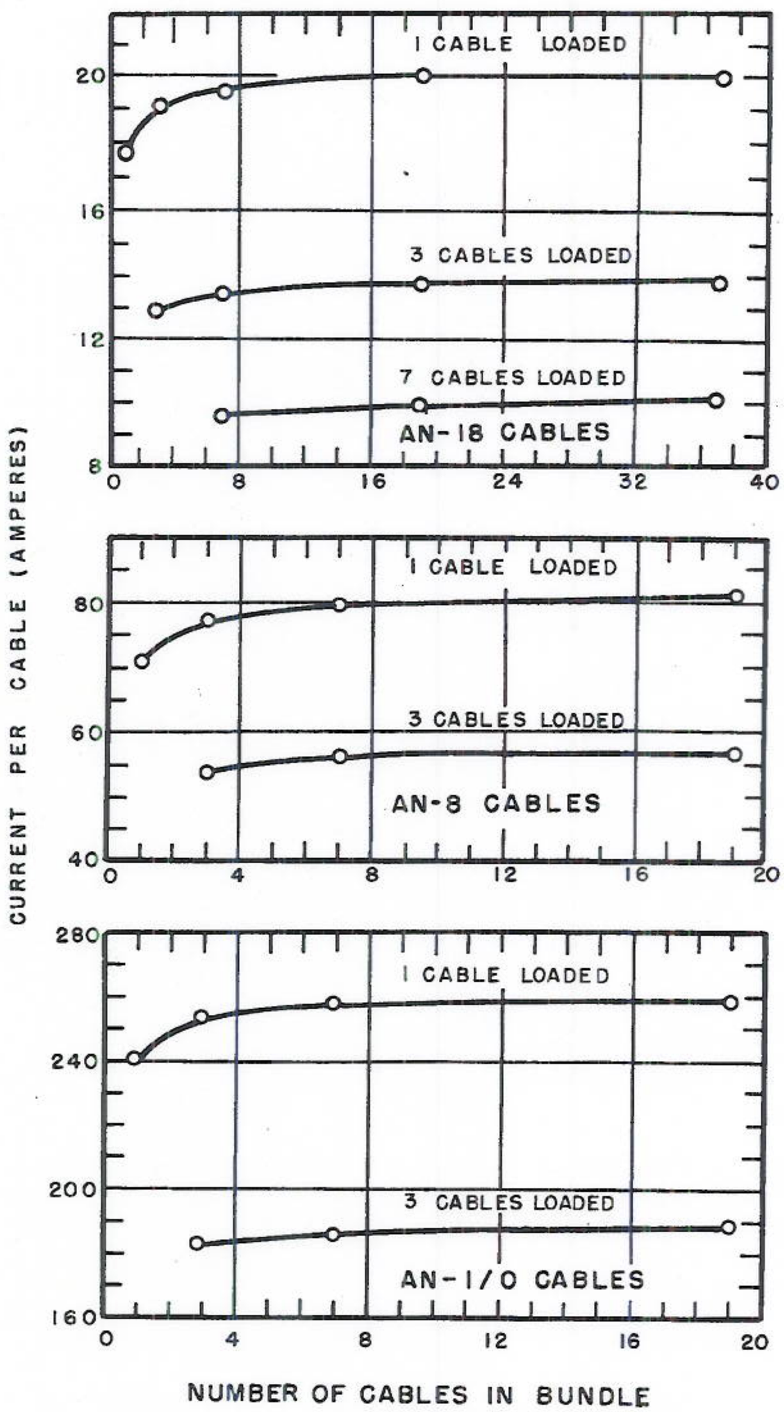

Figure 4 - Effect of the total number of cables in the bundle on current rating. Each point plotted represents the lowest current rating for the specified number loaded. (Temperature rise of the hottest conductor 40°C. Ambient air temperature 25°C. Sea level.)

Current and Temperature Rise

The temperature rise of the hottest conductor in the bundle is proportional to the square of the current per loaded cable for all fully loaded, tight bundles over the range of temperature rise investigated (approximately 20° to 80°C). Temperature rise values calculated with this relation agreed with measured values to within three percent. The experimentally determined current and temperature rise for fully loaded bundles of sizes AN-18, AN-8, and AN-1/0 are shown in Figures 5, 6, and 7.

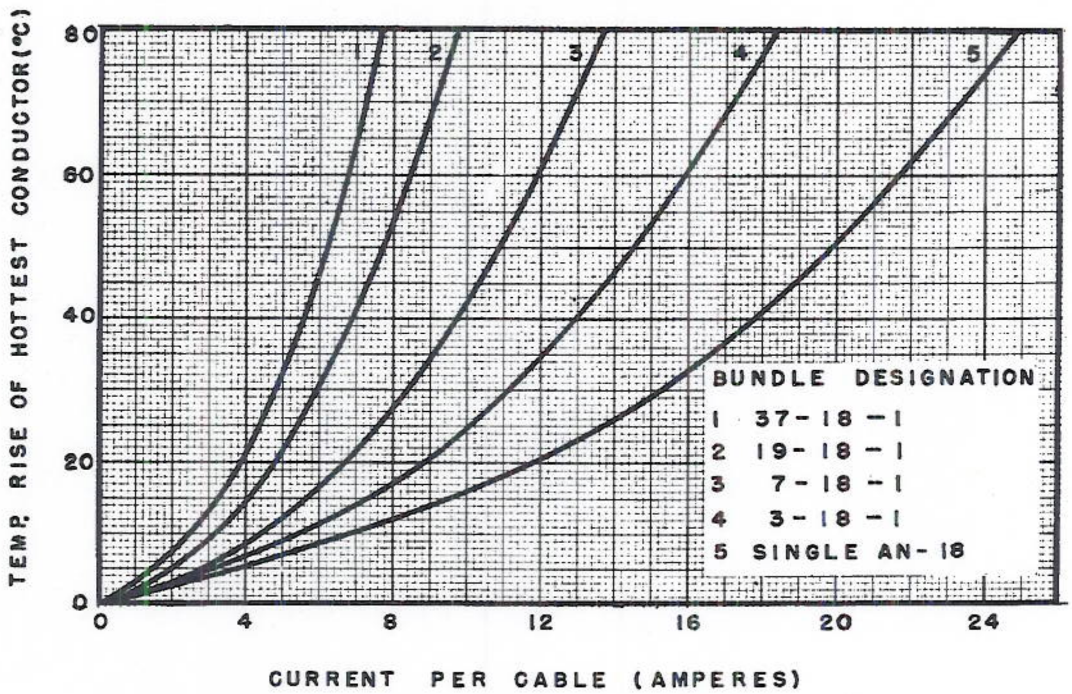

Figure 5 - Temperature rise of the hottest conductor as a function of current per cable for tight, fully loaded, uniform bundles of AN-18 cables. (Ambient air temperature 25°C. Sea level.)

Summary

It has been noted that current capacity is not a single-valued function of the number of cables loaded, and that the multiple values result from the fact that there is more than one position for each given number of cables loaded. A single-valued function can be obtained for any given bundle by considering only those positions (corresponding to poorest heat transfer conditions) which give the lowest ratings. Such experimentally determined curves, marked "(1)," are shown in Figures 8, 9, and 10 for tight bundles 37-18-1, 19-8-1, and 19-1/0-3.

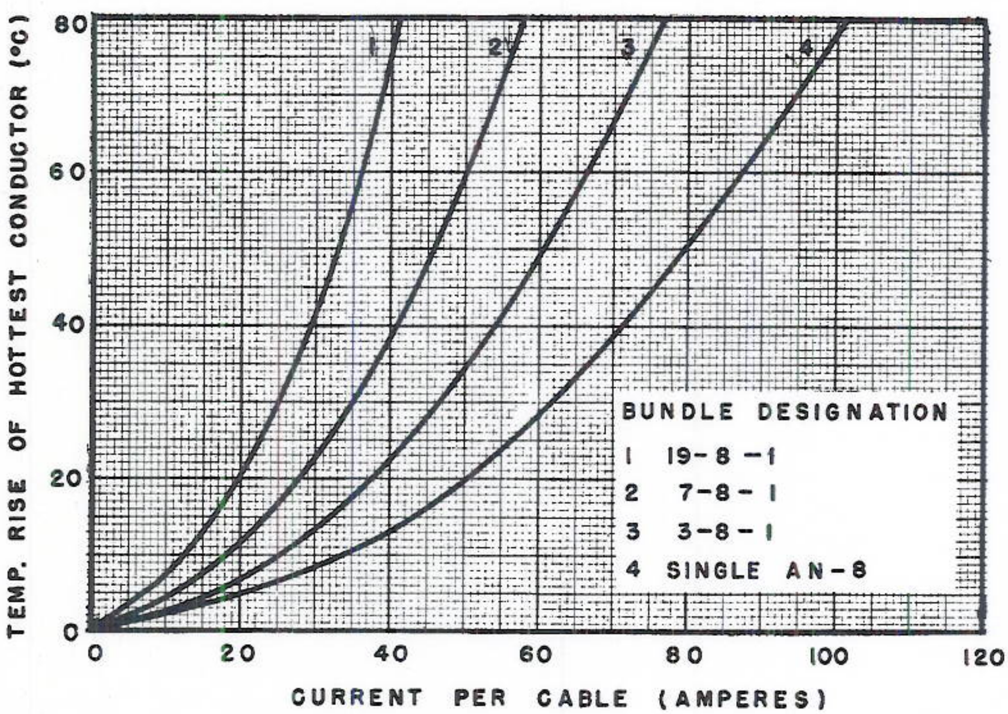

Figure 6 - Temperature rise of the hottest conductor as a function of the current per cable for tight, fully loaded, uniform bundles of AN-8 cables. (Ambient air temperature 25°C. Sea level.)

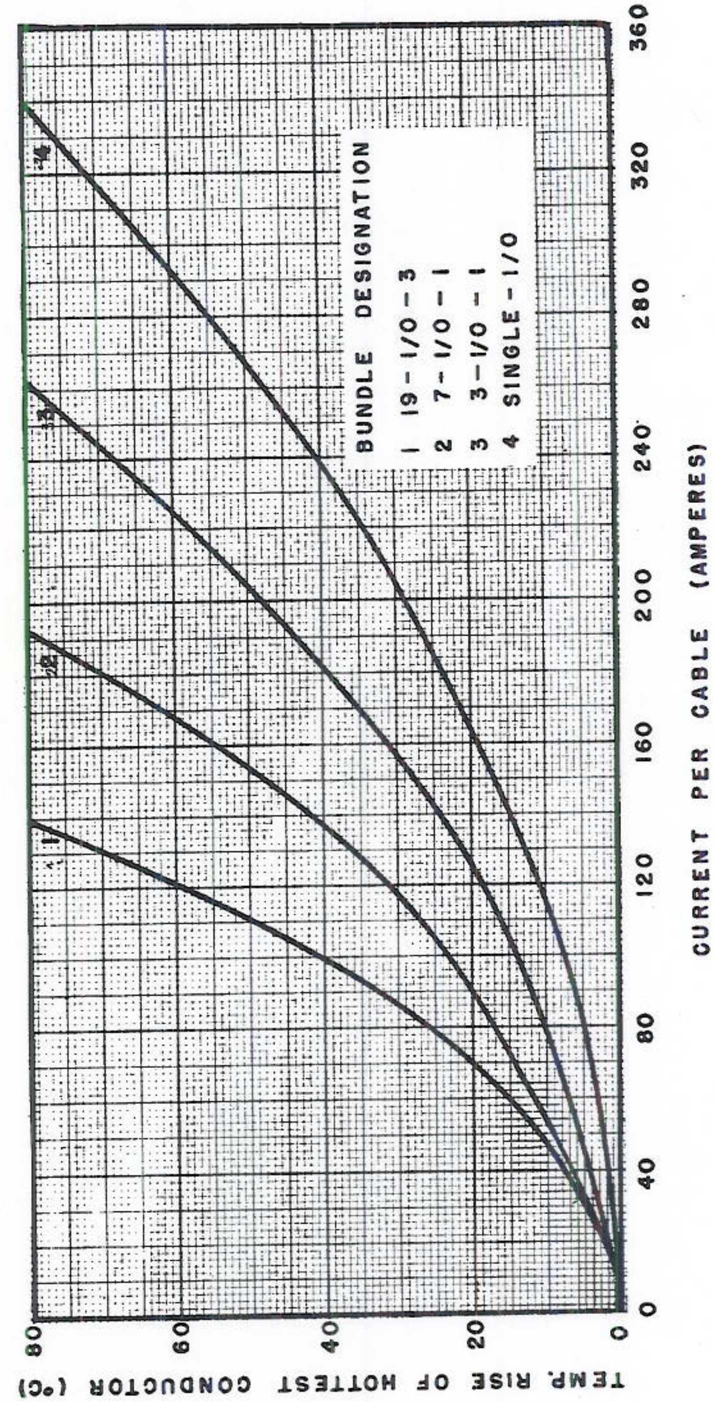

Figure 7 - Temperature rise of the hottest conductor as a function of the current per cable for tight, fully loaded, uniform bundles of AN-1/0 cables. (Ambient air temperature 25°C. Sea level.)

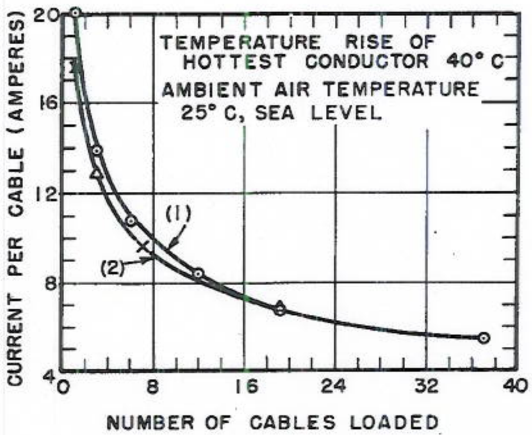

Figure 8 - (1) Lowest current ratings for a tight bundle of 37 AN-18 cables. (2) Current ratings for fully loaded, tight bundles of AN-18 cables.

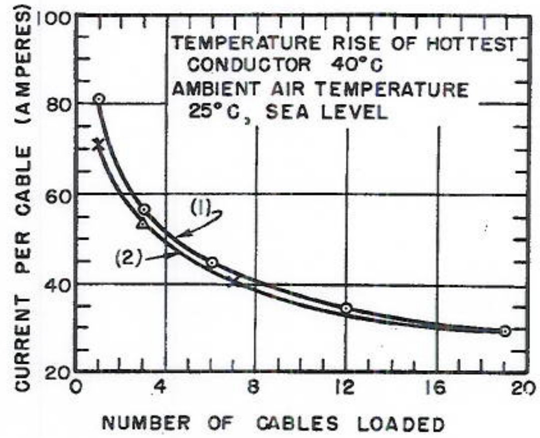

Figure 9 - (1) Lowest current ratings for a tight bundle of 19 AN-8 cables. (2) Current ratings for fully loaded, tight bundles of AN-8 cables.

It was shown that the current rating for a given number of cables loaded is a minimum when the total number of cables in the bundle equals the number loaded. If current rating based on fully loaded bundles (bundles in which every cable carries current) is plotted as a function of the number of cables loaded, the minimum curve for the tight-bundle condition is obtained. Such curves, marked "(2)," are shown in Figures 8, 9, and 10 for AN cable sizes 18, 8, and 1/0, respectively. These curves may be described by the approximate relation

$$I_n = I_1/n^{\alpha}$$

where I_1 is the current which may be carried by a single cable in air, n is the number of cables in the fully loaded bundle and I_n is the current per cable for the n cables. The exponent α has the values 0.324, 0.298, and 0.299 for bundles of AN-18, AN-8, and AN-1/0 cables, respectively. Minimum current ratings for tight bundles of typical aircraft cables are given in Figure 11; the curves for AN sizes 18, 8, and 1/0 are based on actual measurements, the remaining curves being interpolated from these. The single-cable current values used in the interpolated curves are based on Military Specification, MIL-W-5088.

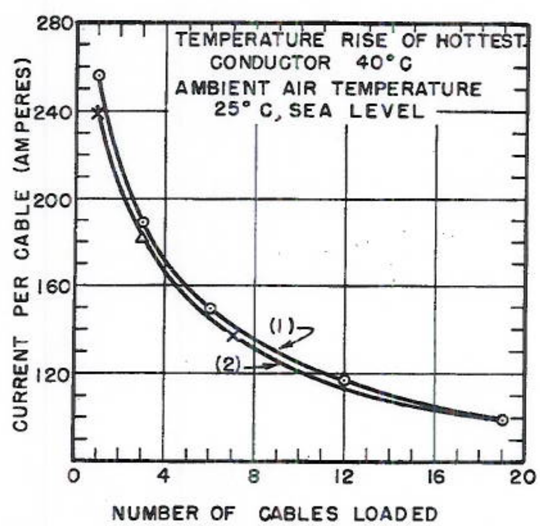

Figure 10 - (1) Lowest current ratings for a tight bundle of 19 AN-1/0 cables. (2) Current ratings for fully loaded, tight bundles of AN-1/0 cables.

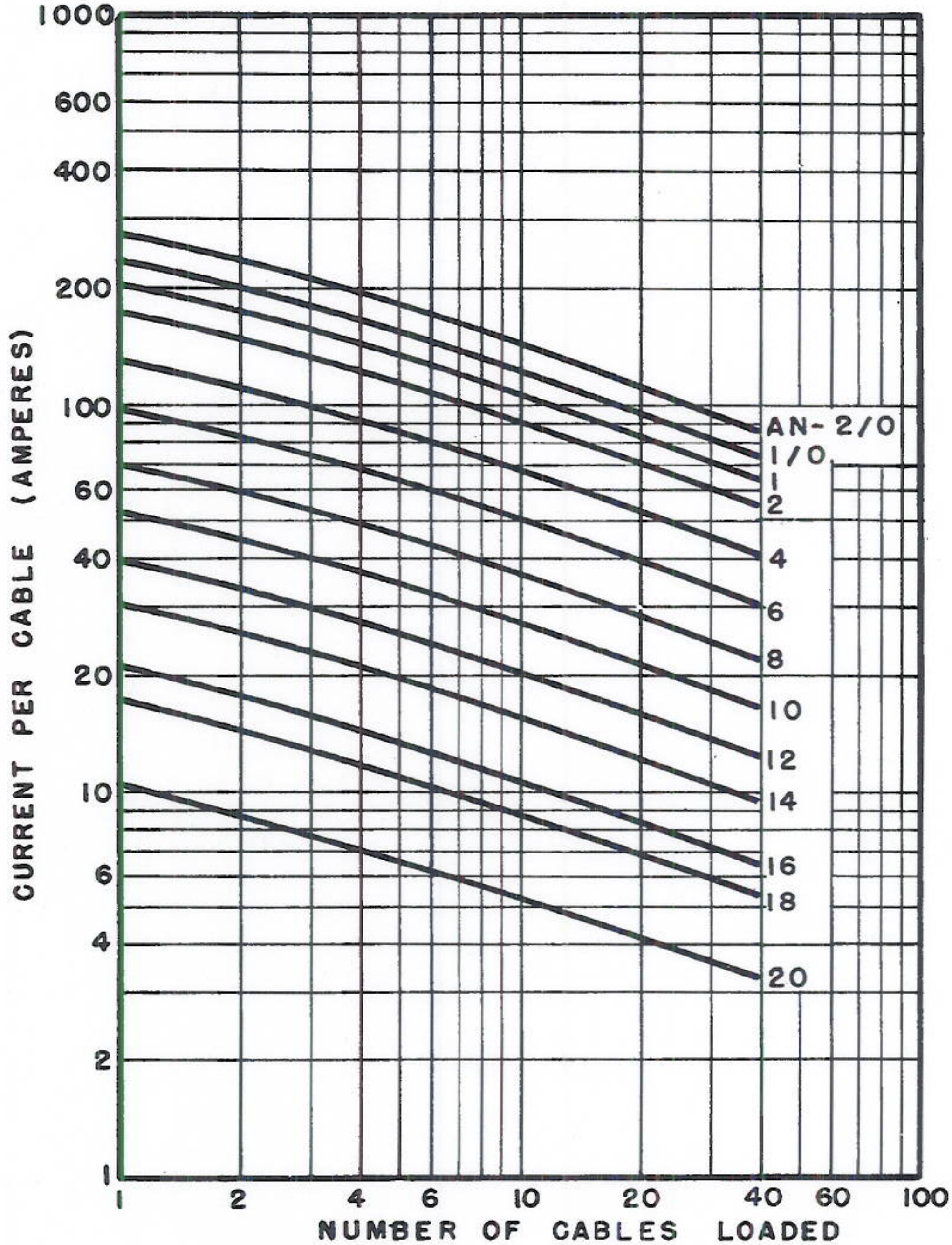

Figure 11 - Current ratings for tight uniform bundles of typical aircraft cables when all cables carry the same current. (Temperature rise of hottest conductor 40°C. Ambient air temperature 25°C. Sea level.)

EMPIRICAL RESULTS (Loose Bundles)

As the interval between ties is increased, that is, as the bundle is loosened, current capacity changes gradually. The magnitude and sign of the change depends on the number and position of the loaded cables. The experimental results for bundles of 37 AN-18, 19 AN-8, and 19 AN-1/0 cables are shown in Figures 12, 13, and 14. The position numbers of the loaded cables are indicated for each curve. It may be noted that the interval of tie for which a minimum current capacity is obtained depends upon the number of cables loaded. Current values for the poorest heat-transfer conditions are shown as a function of the number of cables loaded in Figures 15, 16, and 17 for loose bundles of 37 AN-18, 19 AN-8, and 19 AN-1/0 cables by curves marked "(2)."

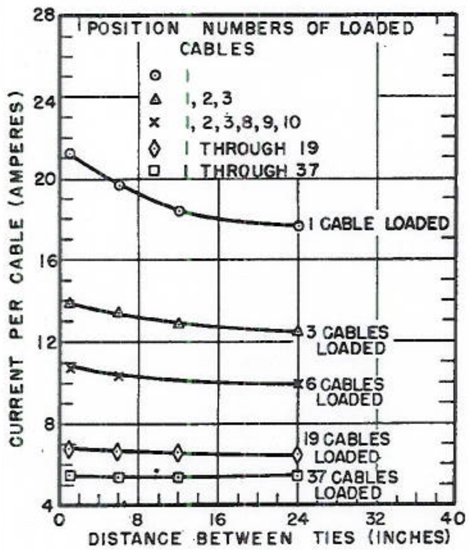

Figure 12 - Effect of bundle tightness on current rating for 37 AN-18 cables. (Temperature rise of hottest conductor 40°C. Ambient air temperature 25°C. Sea level.)

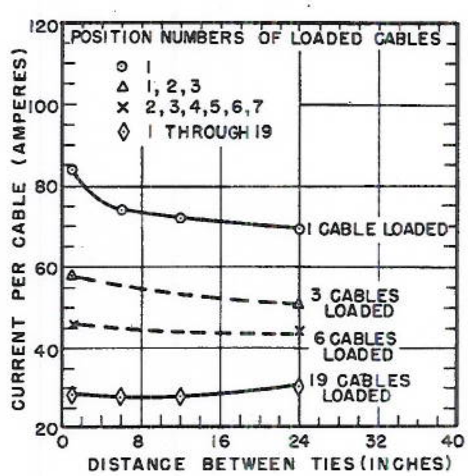

Figure 13 - Effect of bundle tightness on current rating for 19 AN-8 cables. (Temperature rise of hottest conductor 40°C. Ambient air temperature 25°C. Sea level.)

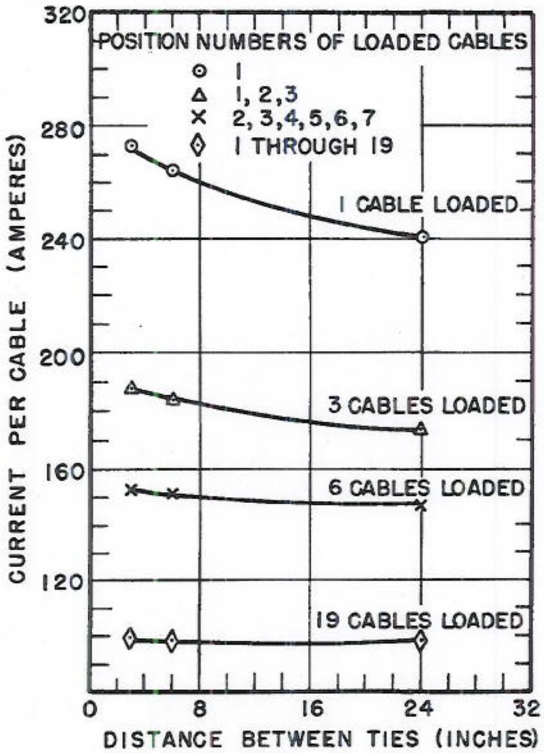

Figure 14 - Effect of bundle tightness on current rating for 19 AN-1/0 cables. (Temperature rise of hottest conductor 40°C. Ambient air temperature 25°C. Sea level.)

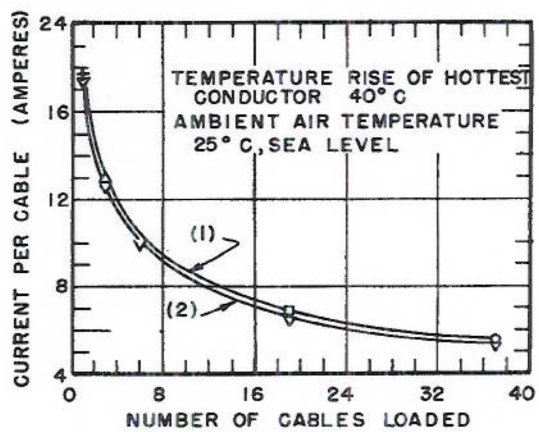

Figure 15 - (1) Current ratings for tight, fully loaded bundles of AN-18 cables. (2) Lowest current ratings for loose bundles of 37 AN-18 cables (6-, 12-, or 24-inch ties).

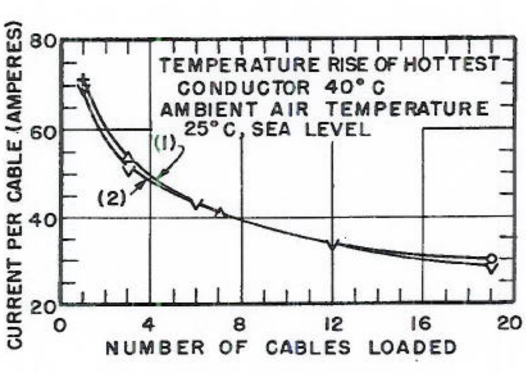

Figure 16 - (1) Current ratings for tight, fully loaded bundles of AN-8 cables. (2) Lowest current ratings for loose bundles of 19 AN-8 cables (6-, 12-, or 24-inch ties).

The changes in current capacity which occur when the bundle is loosened may be explained qualitatively in terms of the modified heat-transfer conditions. Two opposing processes occur as the bundle is loosened: (1) the effective thermal conductivity of the bundle decreases, and (2) the conditions for heat transfer by convection and radiation at the outer bundle surface improve, that is, the effective surface area increases. For the case of one cable at the center loaded, the deterioration in heat conduction is the predominant effect, and the current rating is reduced when the bundle is loosened. For the case in which the entire outer layer and no other cables carry current, the only effect to be considered is that of the improved heat transmission at the outer surface. Consequently, the current rating for this case increases as the bundle is loosened. Finally, if every cable in the bundle carries current, the two effects nearly compensate each other, and so the current capacity is nearly independent of bundle tightness for the range investigated. In all cases, if the cables were to be separated further than observed experimentally, the current in each loaded cable would begin to increase and approach its value for a single cable in air.

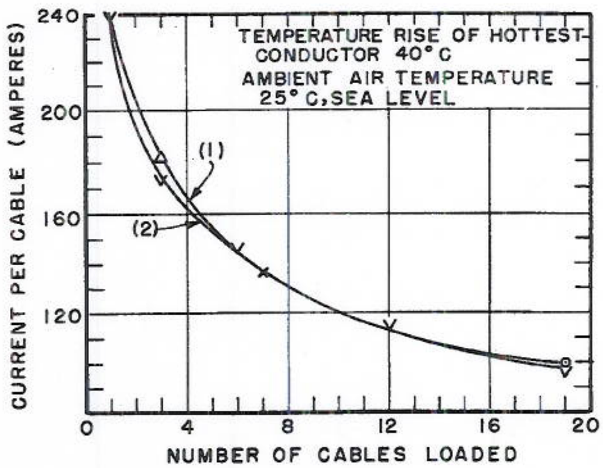

Figure 17 - (1) Current ratings for tight, fully loaded bundles of AN-1/0 cables. (2) Lowest current ratings for loose bundles of 19 AN-1/0 cables (6-, 12-, or 24-inch ties).

TIGHT VS. LOOSE BUNDLES

Figures 15, 16, and 17 compare the minimum tight- and loose-bundle ratings. The loose-bundle conditions give the absolute minimum current rating for each number of cables loaded. It was observed that the minimum values for bundles bound by six-inch ties are as much as three percent below the tight-bundle minimum values while the lowest values of bundles bound by 24-inch ties are as much as six percent below the minimum tight-bundle values.

ANALYSIS OF HEAT FLOW AND CALCULATION OF CURRENT RATINGS

The possibility of calculating ratings for uniform bundles on the basis of an analysis of the heat flow in the bundle and to its surroundings was suggested by the physical symmetry of tight bundles of 7, 19, and 37 cables and by the small difference observed between the minimum ratings of tight and loose bundles.

In order to describe the heat flow analytically, it must be possible to assign a definite thermal conductivity, radiation coefficient, and convection coefficient to a bundle. The thermal conductivity, K, was found by treating the bundle as a cylinder and measuring the quantities required by the heat conduction relation

$$K = \frac{I^2 R_1 \log_e(b/a)}{2\pi(T_1 - T_S)}$$

when current was flowing through the center cable (position 1) only. The symbols in the equation are:

K = thermal conductivity

I = current

R_1 = conductor resistance per unit length at temperature T_1

b = average over-all radius of the bundle

a = radius of the center conductor

T_1 = temperature of the center conductor

T_S = average temperature of the outer bundle surface

The values of K calculated from the data are 0.0040, 0.0050, and 0.0070 watts $in^{-1}\ {}^{\circ}C^{-1}$ for bundles of AN-18, 8, and 1/0, respectively.

The radiation coefficient, r, defined as the heat radiated in unit time by unit area for one degree difference in temperature between the bundle and the surrounding walls, may be computed from the relations governing the net radiation transfer between a body and its surroundings. Because the outer surface of the bundle is indented, there is some uncertainty as to the precise bundle surface area. It can be shown that, as a good approximation, the radiating area per unit length is numerically equal to the circumference of the circle circumscribing the bundle. A plot of the radiation coefficient which assumes a surface emissivity of 0.9 is given in Figure 18. The values for r shown in the figure are obtained from the relation

$$r = \frac{Se\left(T_{sk}^4 - T_{ak}^4\right)}{T_{sk} - T_{ak}}$$

where S = Stefan's constant

e = emissivity of cable surface

T_{sk} = average temperature of the bundle surface in degrees absolute

T_{ak} = temperature of the surrounding walls in degrees absolute. It will be assumed that the wall temperature is the same as that of the air at a point where the gradient has become negligible.

The convection coefficient, defined as the heat transferred by natural convection in unit time by unit area for one degree difference between the bundle surface temperature and the ambient air temperature, was determined empirically from bundle measurements. The results are shown in Figure 19 where the convection coefficient is plotted as a function of the average diameter of the bundle surface.

It is now possible to calculate the current per cable of tight, fully loaded bundles of 7, 19, or 37 cables with the aid of the measured thermal parameters by treating the bundle as a series of concentric cylindrical layers, each of which contributes to the heat flow. The method of calculating the current per cable for a given maximum conductor temperature rise will be described by considering a uniform bundle of 19 cables. A cross-section of this bundle, showing the approximate boundaries for heat transfer, is given in Figure 20.

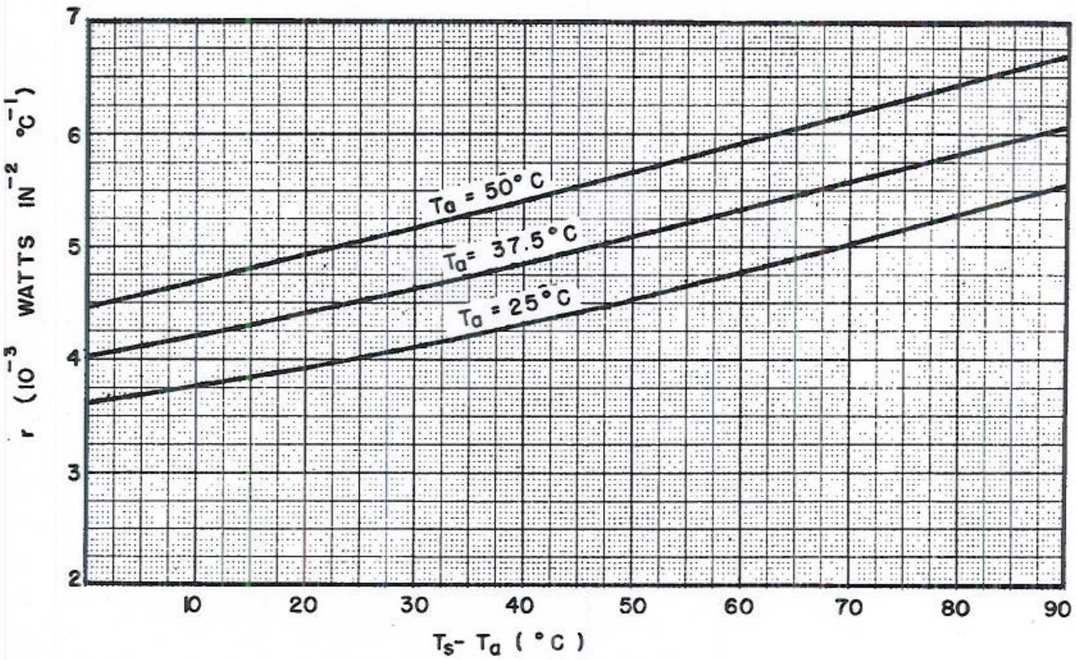

Figure 18 - Radiation coefficient, r, versus average surface temperature rise, $T_s - T_a$, for three ambient temperatures, T_a

The heat produced by the center cable is conducted to the center of the first layer. The rate of heat flow per unit length in this region is given by the relation

$$I^2R_1 = \frac{2\pi K (T_1 - T_2)}{\log_e (r_2/r_1)} \qquad (1)$$

where I = current per cable

R_1 = conductor resistance per unit length at temperature T_1

K = effective bundle thermal conductivity

T_1 = temperature of the center conductor, arbitrarily assigned

T_2 = average temperature of the six conductors in the first layer

r_1 = conductor radius

r_2 = radial distance to the center of the conductors of the first layer.

The approximation is now made that the heat produced by the six cables of the first layer is added to that from the center cable at r_2. This energy is conducted to the mean center of the second layer, r_3. The relation governing the flow of heat from r_2 to r_3 is

$$I^2(R_1 + 6R_2) = \frac{2\pi K(T_2 - T_3)}{\log_e (r_3/r_2)} \qquad (2)$$

where R_2 = conductor resistance per unit length at average temperature, T_2

T_3 = average conductor temperature of the 12 cables in the second layer

r_3 = mean radial distance to center of the conductors in the second layer.

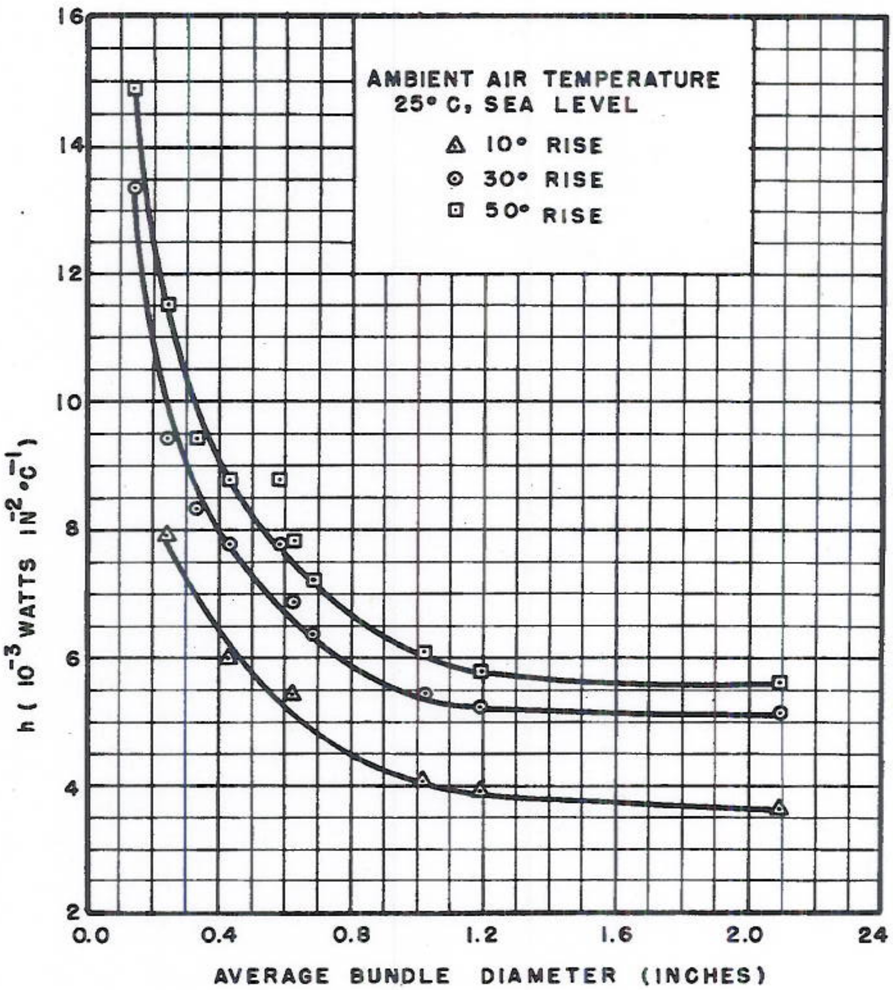

Figure 19 - Convection coefficient, h, versus average bundle diameter for three values of average surface temperature rise

The further approximation is made that the heat produced by the twelve cables of the second layer is added to that of seven interior cables at r_3, and the total energy is conducted to the outer surface. In the region from r_3 to r_4 we have

$$I^2(R_1 + 6R_2 + 12R_3) = \frac{2\pi K\,(T_3 - T_S)}{\log_e\,(r_4/r_3)} \quad (3)$$

where R_3 = conductor resistance per unit length at average temperature, T_3

T_S = average bundle surface temperature

r_4 = average radius of bundle periphery. An approximate value of r_4 may be found by subdividing a representative section of the periphery into a number of equal segments and taking the average of the radial distances to the ends of each segment. For example, in the case of the bundle of 19 cables shown in Figure 20, ABC and CDE are examples of representative sections. If ABC is subdivided into a number of equal elements, the average of the distances from the bundle center to the ends of each segment (two distances for each segment) gives the average radius of the bundle periphery. The same result is obtained if the computation is made for CDE or any other of the representative sections.

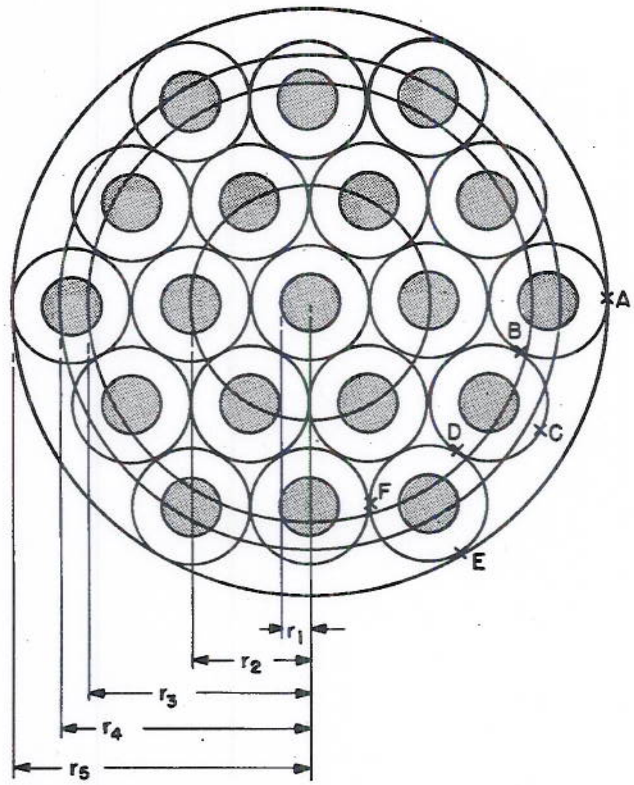

Figure 20 - Heat transfer boundaries for a bundle of 19 cables

At the outer bundle surface, heat is transferred by convection and radiation to the surrounding air and walls. The rate of heat transfer can be stated as

$$I^2(R_1 + 6R_2 + 12R_3) = 2\pi\,(r_4 h + r_5 r)\,(T_S - T_a) \quad (4)$$

where h = convection coefficient

r_5 = radius of the circle which circumscribes the bundle = $2.5\,r_2$

r = radiation coefficient

T_a = ambient air temperature, i.e., temperature of the air at a point where the temperature gradient has become negligibly small.

The current required must satisfy Equations (1), (2), (3), and (4) simultaneously. In these equations the unknown quantities, in addition to the current, are T_2, T_3, T_S, R_2, R_3, R_4, h, and r, the latter five quantities being dependent on the three preceding. In order to find I, the method of successive approximations is used, i.e., one value of I is assumed and substituted in turn in Equations (1), (2), and (3). By this means one determines a set of values of T_2, T_3, T_S, R_2, R_3, and R_4. The values of r and h corresponding to $T_S - T_a$ and bundle diameter may now be selected from Figures 18 and 19. Finally, a value of I can be computed with Equation (4). If this value agrees with the one assumed initially, the correct current has been found. If the two currents differ, other assumed values must be tried and the calculations repeated. The number of trial values required may be limited to two or three by plotting the current calculated by Equation (4) as a function of the assumed current. The intersection of this curve with the straight line, I (calculated) = I (assumed), gives the desired current. The extension of the method to bundles consisting of an integral number of layers is self-evident. Computation details for a bundle of 19 AN-18 cables are given in Appendix II.

The current necessary to produce a 40°C rise in the hottest conductor was calculated for a series of bundles by the method described. The results of these calculations and the currents observed experimentally are given in Table 4.

TABLE 4

Bundle Designation	Calculated Current (Amperes)	Measured Current (Amperes)
7-18-1	9.90	9.65
19-18-1	6.99	6.90
37-18-1	5.45	5.50
7-8-1	41.5	40.6
19-8-1	28.4	29.5
7-1/0-1	135	137
19-1/0-3	94.5	99.0

CONCLUSIONS

Detailed and quantitative information has been made available concerning several of the factors affecting current rating and heat transfer. Some of the data, for example, bundle convection coefficients and the range of thermal conductivity, are applicable not only to uniform bundles but also to mixed bundles (bundles composed of cables of more than one size). Two factors which cannot be expressed easily in quantitative form, the position of the loaded cables and bundle tightness, can be taken into account for uniform-bundle ratings. The conclusions which follow are valid for the range of cable and bundle size investigated. A given rise in the temperature of the hottest conductor is to be assumed.

1. The current per cable decreases as the number of cables loaded increases and obeys the approximate relation

$$I_n = \frac{I_1}{n^{\alpha}} \qquad (0.29 < \alpha < 0.33)$$

for tight, fully loaded, uniform bundles.

2. The current per cable for a given number loaded depends on the position of the loaded cables within the bundle. Variations up to 30 percent in current per cable for a given number loaded can be produced by changing the positions of the loaded cables within the bundle.

3. The current per cable for a given number loaded increases as the total number of cables in the bundle increases and approaches a maximum value.

4. For the tight-bundle condition, the current per cable for a given number of cables loaded is a minimum when the number of cables loaded equals the total number of cables in the bundle.

5. The minimum current per cable for each number of cables loaded for the case of the large, loosely bound bundle (19 or 37 cables) was as much as six percent below the minimum tight-bundle values.

6. The effects of the position of the loaded cables within the bundle and of the total number of cables in the bundle on current rating for a given number loaded may be neglected if ratings are based on conditions which give the minimum current values. The condition for tight bundles which gives the poorest rating for a given number loaded is the fully loaded bundle. Although the loose-bundle condition gives lower current values than the tight-bundle condition, ratings for uniform bundles may be based on those for the tightly laced condition provided that a valid derating factor for the loose-bundle condition is known. The magnitude of derating for the range of loose bundles investigated has been indicated.

7. A method for calculating the current per cable necessary to produce a given temperature rise for uniform bundles of 7, 19, or 37 cables has been described. Current ratings for bundles with a total number of cables between 1 and 37 may be found by interpolation from the calculated values. An estimated accuracy of 10 percent is attainable for cylindrical-shaped, uniform bundles containing up to 37 cables.

8. Uniform bundle ratings may be applied directly to mixed bundles in which the cables loaded simultaneously are of a single size.

9. Temperature rise for fully loaded, tight, uniform bundles is directly proportional to the square of the current per cable for the range of temperature rise observed.

10. Although certain parameters have been fixed throughout the discussion (for example, the ambient air temperature at 25°C, the maximum conductor temperature rise at 40°C, and the air pressure at sea level value) the results and conclusions presented here may easily be extended to other values.

* * *

APPENDIX I
MEASUREMENTS

In all tests, measurements were taken of current, conductor resistance, conductor temperature, and ambient air temperature after thermal equilibrium had occurred. In the case of tight bundles, surface temperature was measured also. The equilibrium condition was arbitrarily defined to exist when the temperature rise of the hottest conductor changed less than 0.1°C in 15 minutes, provided that both the current and the ambient air temperature remained constant. For the range of bundles investigated, the time required for equilibrium varied from 45 minutes to four hours.

The source of current, a 6000-ampere-hour battery, gave a current stable to within 0.04 percent once thermal equilibrium of the circuit was reached.

All tests were conducted in a draft-free, thermally insulated chamber measuring 9 by 12 by 8 feet. The chamber was able to maintain a nearly constant ambient temperature in spite of the fact that the power dissipated by the bundles approached 1000 watts. The maximum rate of change in ambient temperature in the chamber was observed to be less than 0.2°C in 15 minutes.

The bundles were suspended as shown in Figure 21 so that the relative positions of the component cables were maintained throughout the bundle length. To assist in assembling the bundle, cable guides were used. Since all the loaded cables were to carry the same current, the cables were brought to terminal boards, which provided a convenient means of connecting any combination in series.

The test section was situated at the center of the ten-foot bundle. It is believed that the three feet of bundle at each end of the test section was sufficient to insure a constant temperature along the length of each cable in the region of the test section.

Cable resistances were determined by comparing the measured voltage drops across the four-foot test sections with that across a Leeds and Northrup standard shunt. Conductor temperature was then calculated by the change-in-resistance method. Tests on sample cables indicated that the temperature coefficient of resistance for 20°C was 0.00395. It is estimated that measurements of conductor temperature rise were accurate to within 1 percent.

It was not practical to measure the temperature of every conductor in the larger bundles. In most cases, temperatures of the center conductor and three conductors in each layer were measured. For example, in bundle 19-8-1 temperatures of cables 1, 2, 3, 5, 8, 9, and 14 were measured.

Considerable difficulty was experienced in devising a method of measuring surface temperature. Since temperature varied over the bundle circumference some means of averaging these temperatures was needed. In addition, the temperature gradient of the air close to the bundle surface was very large, so that any temperature measuring device had to be an integral part of the surface. After several different techniques had been tried

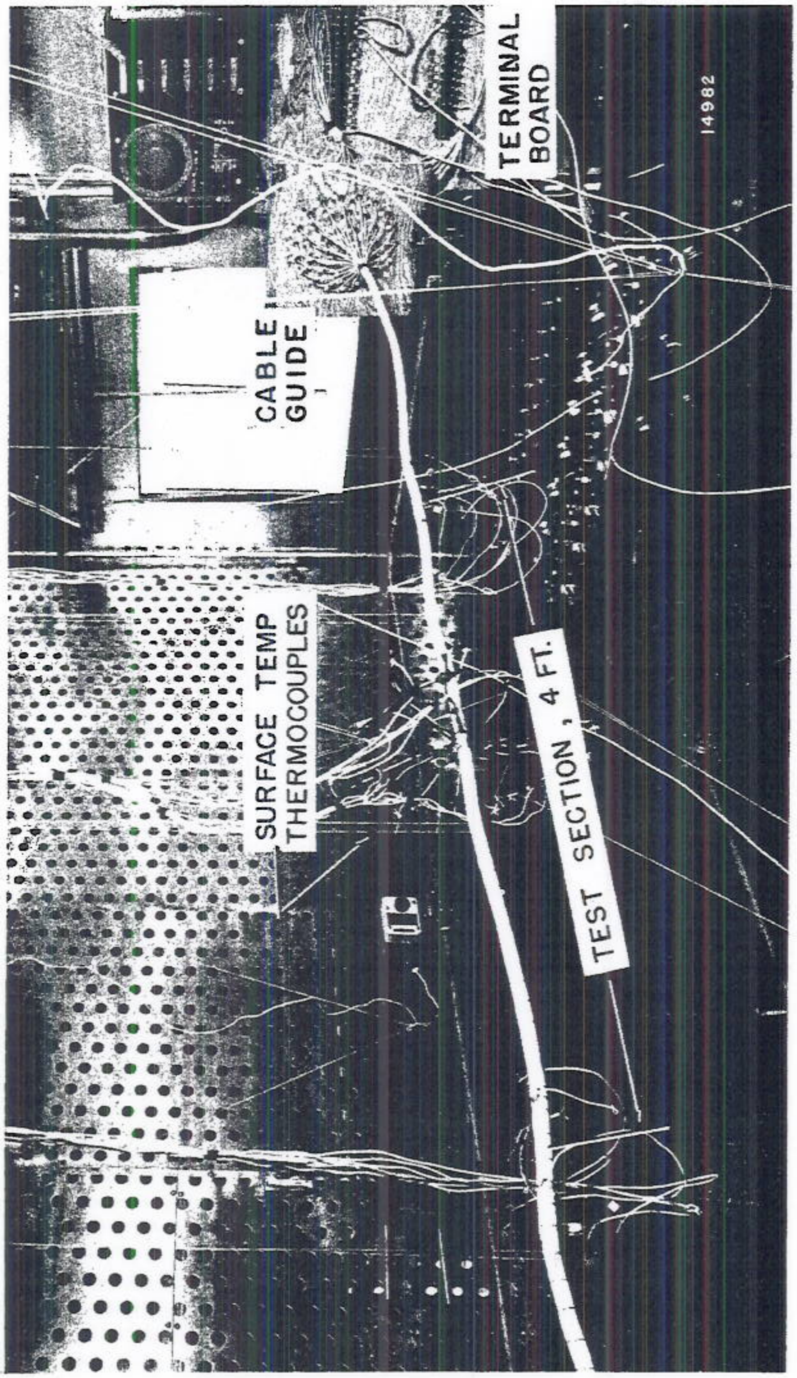

Figure 21 - Experimental setup for measurements on bundles of aircraft cables

it was decided to employ copper-constantin thermocouples constructed from AWG 40 wire. These were imbedded just beneath the surface at the center of the exposed portion of each outer cable. It is estimated that the surface temperature measurements were accurate to within 3°C.

The voltages from the temperature measuring devices and from the standard shunts were measured by a Leeds and Northrup Type K-2 potentiometer with a Leeds and Northrup #2285 galvanometer to indicate balance. Conductor and over-all diameters were determined by averaging twenty micrometer readings.

* * *

APPENDIX II
CALCULATION DETAILS FOR BUNDLE 19-18-1

To determine: I, current per cable, when every cable in the bundle carries current simultaneously

Given: $T_1 = 65°C$ $T_a = 25°C$

Conductor resistance per inch at 20°C = $R = 0.503 \times 10^{-3}$ ohm in^{-1}

Temperature coefficient of resistance = $\alpha = 0.00395$ at 20°C

$K = 0.0040$ watt in^{-1} °C^{-1}

$r_1 = 0.0242$ in. $r_2 = 0.104$ in.

$r_3 = 0.194$ in. $r_4 = 0.216$ in. = average of the radial distances to A, B, C, and D shown in Figure 20

$r_5 = 0.259$ in.

From Equation (1)

$$T_2 = T_1 - I^2R_1 \log_e(r_2/r_1) \qquad (5)$$

Assume that I = 7.5 amperes. Substituting in (5), we obtain

$$T_2 = 63.07°C \text{ and}$$

$$R_2 = R\left[1 + \alpha(63.07 - 20)\right] = 0.589 \times 10^{-3} \text{ ohm in}^{-1}$$

Equation (2) gives

$$T_3 = T_2 - \frac{I^2(R_1 + 6R_2)}{2\pi K} \log_e(r_3/r_2) \qquad (6)$$

$$T_3 = 57.31°C \text{ and}$$

$$R_3 = 0.577 \times 10^{-3} \text{ ohm in}^{-1}$$

Equation (3) gives

$$T_s = T_3 - \frac{I^2(R_1 + 6R_2 + 12R_3)\log_e(r_4/r_3)}{2\pi K} \tag{7}$$

$$T_s = 54.57°C$$

I is now calculated with Equation (4).

$$I = \left[\frac{2\pi(r_4 h + r_5 r)(T_s - T_a)}{R_1 + 6R_2 + 12R_3}\right]^{\frac{1}{2}} \tag{8}$$

which is evaluated for

$$(T_s - T_a) = 54.57 - 25.0 = 29.57°C$$

The radiation and convection coefficients can now be obtained from Figures 18 and 19.

r, for $T_s - T_a = 29.57$, $= 0.00413$ watt in^{-2} °C^{-1}

h, for $T_s - T_a = 29.57$ and bundle diameter $= 2\, r_4$, $= 0.0078$ watt in^{-2} °C^{-1}

Substituting in (8) we find

I = 6.81 amperes

Since the value for I assumed and that calculated by Equation (8) differ, additional trials are required. It is found that when I is assumed to be 6.9 amperes, the current calculated by Equation (8) is 7.02 amperes. If the calculated values are plotted as a function of the assumed values, and if the straight line, I (calculated) = I (assumed) is drawn on the same graph, the intersection at 6.99 amperes gives the desired current. This result is shown in Figure 22.

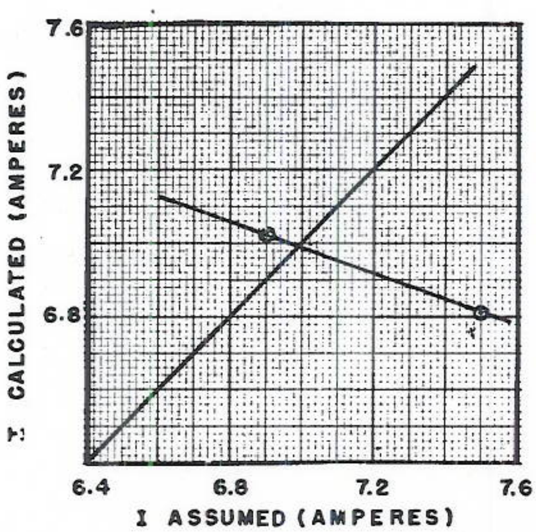

Figure 22 - Graphical solution for current per cable for bundle 19-18-1

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