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FEASIBILITY OF USING ALUMINUM CONDUCTOR CABLES
FOR SHORE-TO-SHIP ELECTRICAL POWER SERVICE

By

David E. Weems

January 1976

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INTRODUCTION

The shore-to-ship electrical power cable currently used by the Navy is a three-conductor cable meeting Military Specification MIL-C-915/6 types THOF-400 and THOF-500. The weight of the type THOF-400 cable is about 6 pounds per foot, resulting in a 100-foot shore-to-ship cable weighing 600 pounds. The type THOF-500 is about 20% heavier than the THOF-400.

Cables manufactured in accordance with MIL-C-915/6 have copper conductors. The current cost of copper is several times more than that of aluminum. In an effort to reduce the weight and cost of shore-to-ship electrical power cables, the Civil Engineering Laboratory (CEL) was requested to determine the feasibility of developing an aluminum conductor shore-to-ship cable. This report contains the results of this investigation.

BACKGROUND

Electrical power is supplied to the ships by shore-to-ship cables, which to meet Navy requirements, must be flexible, carry three-phase power, allow connection and disconnection from the ship, and withstand the environmental conditions on the pier. Cables currently used for this purpose are manufactured in accordance with Military Specification MIL-C-915/6 type THOF-400. These cables (Figure 1) contain three copper conductors each with 2052 strands of 0.014-inch-diameter wire to produce a flexible 400 MCM three-conductor cable. Type THOF-500 cable with 500 MCM conductors is also used where larger currents are required. The THOF-500's cable construction is similar to that of the THOF-400 cable.

In addition, personnel disconnecting these shore-to-ship cables have complained about the high surface temperatures of the cable. High ambient temperatures, high solar heat gain, and internal heat generated by high load currents in the conductors are responsible for these temperatures. The Naval Facilities Engineering Command (NAVFAC) expressed an interest in reducing these surface temperatures. Presently THOF-500 cable is used instead of THOF-400 cable to reduce the surface temperature of the cable.

FEASIBILITY STUDY

Advantages of Aluminum Conductors

The two major advantages of using aluminum, instead of copper, are weight and cost. Aluminum weighs one-half as much as copper for the

same ampacity conductor [1]. A type THOF-400 shore-to-ship cable weighs around 6 pounds per foot. An aluminum conductor cable constructed in the same manner and with the same ampacity would weigh around 4.2 pounds, or a reduction in weight of around 30%.

The cost of aluminum is around one-fifth the cost of copper for the same ampacity; however, the cost of drawing aluminum into wire reduces this cost advantage. Aluminum conductor power cable is about one-half the cost of the same ampacity copper conductor power cable.

Disadvantages of Aluminum Conductors

There are five major disadvantages to using aluminum as the conductor for electrical power: corrosion, cold flow, size, flexibility, and fatigue.

Corrosion. Aluminum, when exposed to air and moisture, will corrode. When corrosion occurs, a thin coating of oxide forms which prevents further oxidation [1]. This process makes the use of uninsulated aluminum conductors practicable.

When aluminum is exposed to moisture in the absence of air, the problem is entirely different. In this case, the Poultice effect will cause the aluminum to rapidly convert to aluminum hydroxide, a whitish powder [1,3]. The aluminum hydroxide is not only a poor electrical conductor, it also has a volume much greater than the aluminum from which it was formed. This increased volume will result in the conductor's insulation being ruptured.

One additional form of corrosion is due to dissimilar materials. Aluminum in direct contact with copper such as would be the case will corrode rapidly due to 0.43-volt electrode potential difference [2]. This problem can be eliminated by using tin plating on the connectors.

Cold Flow. If aluminum is crimped into a copper connector or held in place with brass screws, the aluminum, with its higher coefficient of expansion, will attempt to walk itself out of the fittings as the temperature cycles [2]. To eliminate this problem with crimp connectors, an aluminum connector is used to join aluminum to either copper or aluminum. A compression type of crimp must be used for aluminum conductors to reduce the cold flow problem.

Size and Flexibility. The flexibility of a bar of aluminum is about the same as that of copper. In an electrical power cable, the flexibility is also dependent on the amount of insulation, the number of strands, and the lay of the strands.

The maximum radius in which a cable may be bent is based on the diameter of the cable. Since aluminum has a 50% larger cross section area than copper, the aluminum conductor cable cannot be bent into as sharp a bend as the same ampacity copper conductor cable.

Fatigue. Aluminum wire fatigues about three times faster than copper wire. The breaking of strands at locations where the cable is flexed indicates fatigue failure. This problem is not serious in most electrical power distribution systems, since the cable will not be flexed after the system

is installed. In the case of shore-to-ship cable, where the cable is subjected to frequent flexing, the fatigue problem can pose a real problem.

Aluminum Shore-to-Ship Cable Construction

The major requirements of a shore-to-ship electrical power cable are that it must carry three-phase, 400-ampere, electrical power, and be as light and flexible as possible. The amount of power that must be carried by the cable determines the size of the cable. The copper conductor can be replaced with aluminum to reduce the weight of the cable; however, this replacement increases the size of the cable.

To produce a flexible shore-to-ship cable, the conductor is presently constructed of 2052 copper strands. If aluminum is used as a conductor with the same number of strands the increased cross section of each strand will result in an increase of the overall cable size which will reduce its flexibility.

Cyprus Cable Company and Alcoa Conductor Products Company were contacted to determine the feasibility and cost of manufacturing aluminum conductor shore-to-ship electrical power cable. Both companies stated that they would not attempt to manufacture this type of cable due to the large number of fine aluminum strands.

MIL-C-24368 Connector Interface

Shore-to-ship electrical power cables are terminated in MIL-C-24368 connectors (Figures 2 through 4). These connectors are constructed with a crimp-on copper bus (Figure 2) for each conductor. After the busses are crimped on, the pins are installed (Figure 3) and the busses are potted into the housing (Figure 4). The cable can then be rapidly connected to the receptacles on the pier (Figure 5) and on the ship.

There are two problems with this connector if it is used on aluminum conductors. The material used for the crimp portion of the bus should be the same as the conductor to reduce cold flow. The bus, however, must be copper since the pins are copper. Therefore, for this connector to be used on aluminum conductor cable, the connector must be modified to allow the crimp portion of the bus to be aluminum while keeping copper as the bus material. The connector pins screw into threaded holes in the bus (Figure 3). These holes in the bus are drilled all the way through the material. The hole for the center pin could allow a path for moisture to get to the aluminum conductor in the crimp portion of the bus which would cause the aluminum conductor to corrode.

TEMPERATURE TESTS

Procedure

A 100-foot length of THOF-400 cable was tested to determine the surface temperatures of THOF-400 shore-to-ship cable. The cable was placed on an

asphalt surface with half of its length exposed to the sun and the other half in the shade. A load bank was supplied with 480-volt, three-phase power to generate the required load currents.

The temperatures of the cable were monitored with thermocouples, and their output was recorded on a Brown recorder. The first thermocouple was mounted on the surface of the cable at a point where the cable was exposed to the sun. The second thermocouple was mounted on the surface of the cable at a point where the cable was in the shade. The last thermocouple was mounted at a point where it could record the ambient temperature of the air.

The test setup was made, and the temperatures were allowed to stabilize. The temperatures of the cable were recorded with no current passing through the THOF-400 cable.

A 300-ampere load was applied to the cable. The temperatures of the cable were recorded for a 3-hour period while 300 amperes was being carried by the cable. The current on the cable was then removed to allow the temperature of the cable to stabilize.

The load was then increased until 400 amperes was being carried by the THOF-400 cable. The temperatures of the cable were recorded for a 3-hour period while 400 amperes was being carried by the cable.

Results

The temperatures of the cable stabilized after 2 hours with a constant current being carried by the conductor. Table 1 gives the results of the stabilized temperatures.

Table 1. Results of Temperature Tests

Current in Each Conductor (amp)	Ambient Temperature (°C)	Surface Temperature (°C) of Cable in--	
		Shade	Sun
0	16.7	16.7	30.4
300	16.7	19.4	34.4
400	16.7	22.8	30.6

It is noted that two uncontrollable variables were encountered during the test: wind speed and the intensity of the sunlight.

For the zero current and 300-ampere tests there was a light wind. This wind increased to around 5 mph during the 400-ampere test. Table 1 shows the effects of wind speed variations on the surface temperature of the cable.

The temperature test results are consistent with the values calculated using Reference 5.

Discussion

Electrical power cables constructed in accordance with MIL-C-915/6 are designed with a maximum operating temperature of 75°C. Therefore, the ampacity of a three-conductor copper cable in still air [4] is:

Ambient Temperature (°C)	Current for 400 MCM Cable (Amperes)	Current for 500 MCM Cable (Amperes)
30	425	490
35	395	450
40	370	420
45	340	390
50	310	355

Figures 6 and 7 were calculated for a THOF-400 cable using the formulas in the Appendix [5,6] with the ambient temperature 30°C and no wind. The current for a temperature of 75°C and maximum solar gain in Figure 7 is 435 amperes which compares favorably with the 425 amperes given above.

Figure 6 shows that even with no current being carried by the conductors the surface temperature of the cable can be as much as 19.5°C (35°F) higher than the ambient temperature. In this case with an ambient of 30°C (86°F) the surface temperature can be as high as 49.5°C (121.1°F). Figure 6 shows that reducing the amount of current that the conductors carry will reduce the surface temperature; however, the solar gain of the cable can contribute more than half of the surface temperature rise. Therefore, increasing the size of the conductor more than what is necessary to carry the required current will not appreciably reduce the surface temperature of the cable.

CONCLUSIONS

1. The use of aluminum as the conductors for shore-to-ship cable would reduce the weight of the cable.
2. An aluminum conductor shore-to-ship cable would have a larger cross section than the copper conductor shore-to-ship cable.
3. An aluminum conductor shore-to-ship cable would be less flexible than the copper conductor shore-to-ship cable.
4. Aluminum fatigues faster than copper and would result in strands breaking where the cable is flexed the most.
5. Aluminum must be well protected from the environment. If moisture gets to the conductor, it will corrode rapidly [1].

6. The manufacturers of aluminum conductor electrical power cable do not want to produce an aluminum conductor shore-to-ship cable.

7. The MIL-C-24368 connector must be modified to allow its use with aluminum conductor cable. This modification would require a bus with an aluminum crimp portion and copper where the connector pins are mounted.

8. The surface temperature of shore-to-ship cable may be reduced slightly by increasing the size of the conductor beyond what is necessary to handle the current requirements.

RECOMMENDATIONS

The only advantage of using aluminum as the conductor in shore-to-ship cable is the reduction in the weight of the cable. Since there are several major disadvantages to using aluminum, including the lack of interest from the cable manufactureres, it is recommended that the use of copper for the conductor as shore-to-ship cable be continued.

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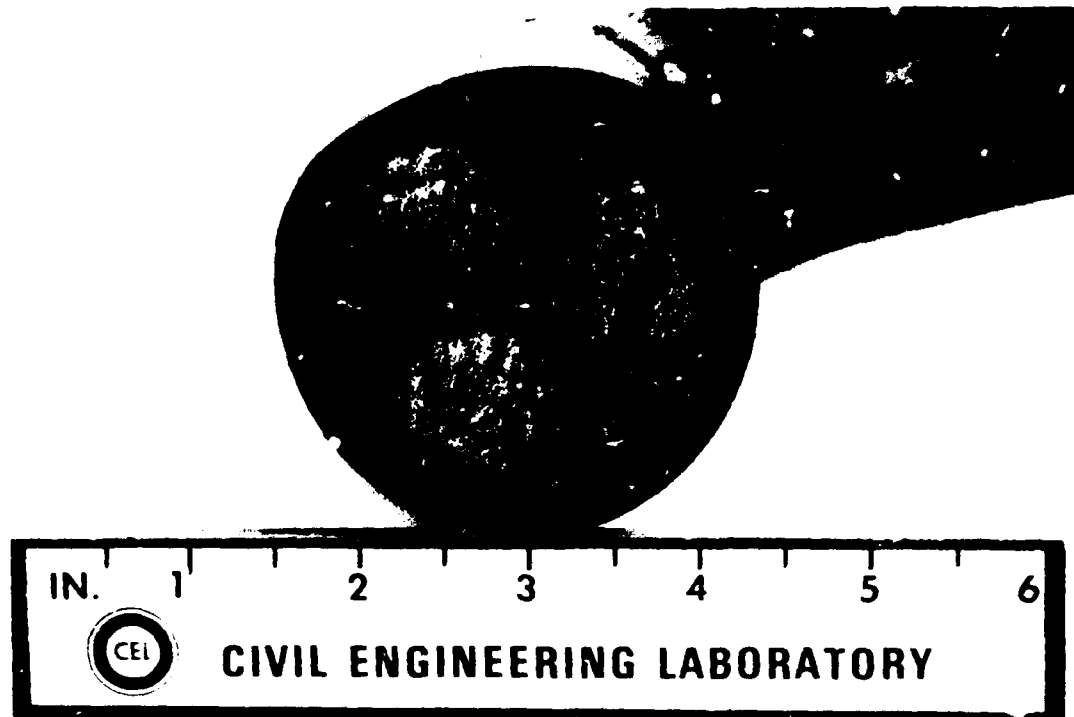


Figure 1. Cross section of THOF-400 shore-to-ship cable.

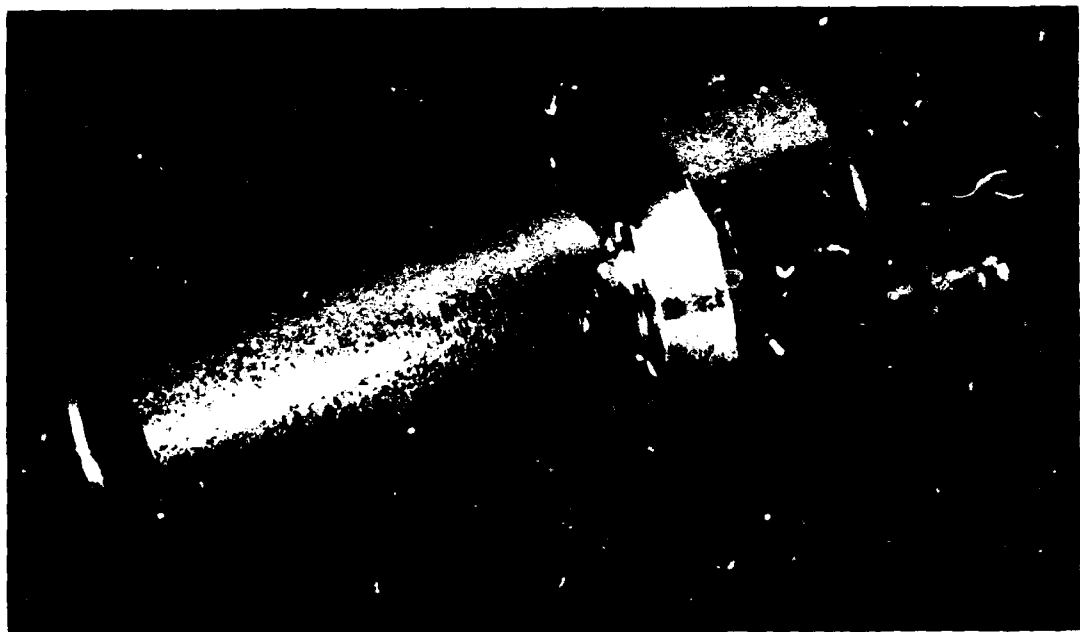


Figure 2. Bus for MIL-C-24368 connector, showing crimp on barrel.

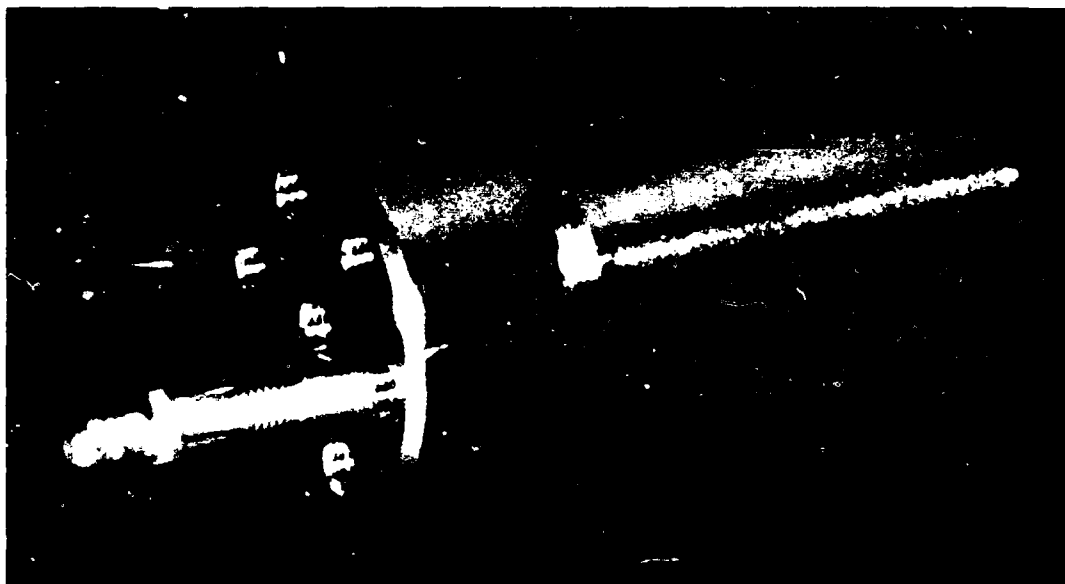


Figure 3. Bus for MIL-C-24368 connector, showing pin installation.

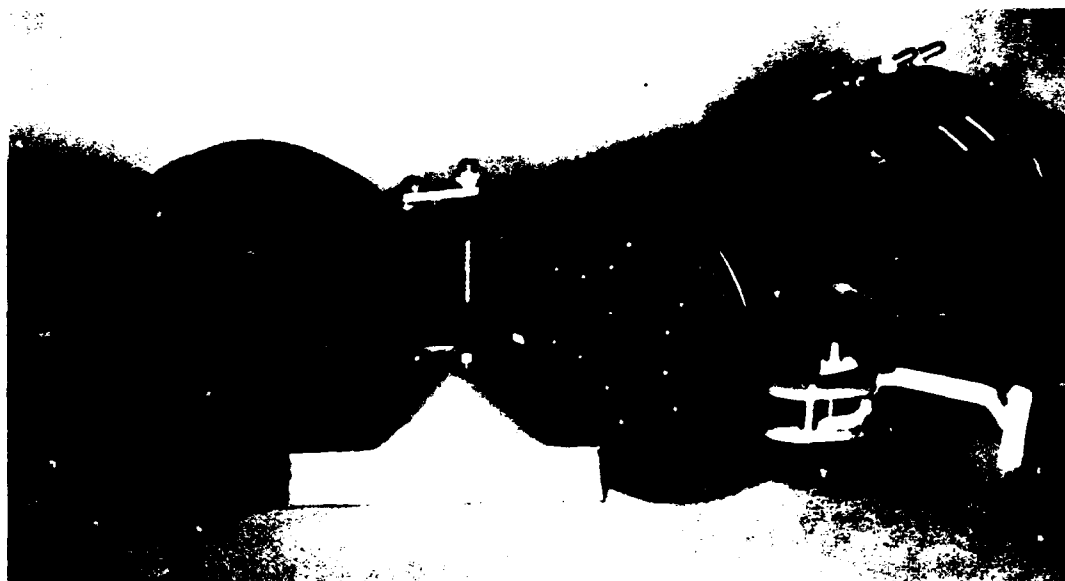


Figure 4. Housing for MIL-C-24368 connector.

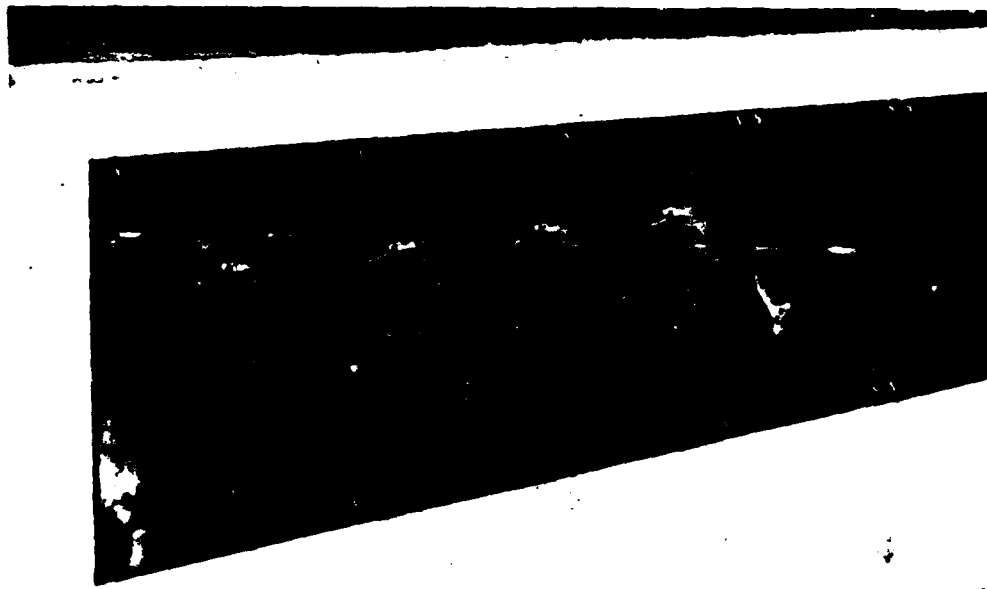


Figure 5. Receptacle for MIL-C-24368 connector installed on pier.

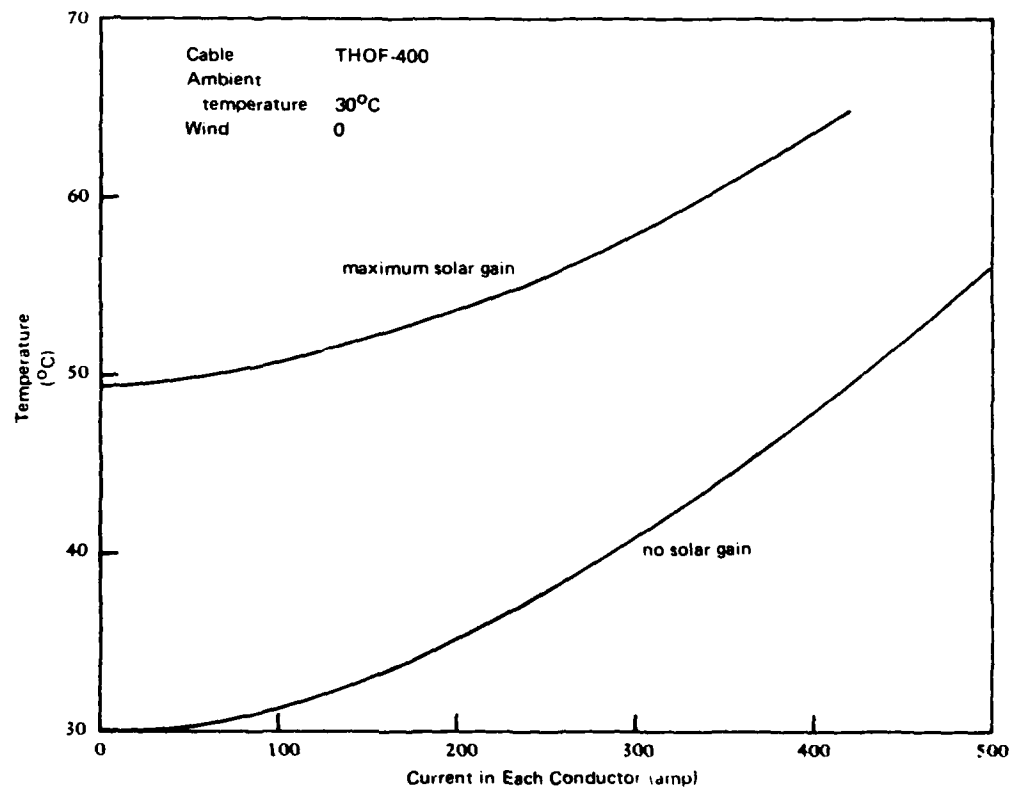


Figure 6. Temperature at surface of cable insulation due to current and solar gain

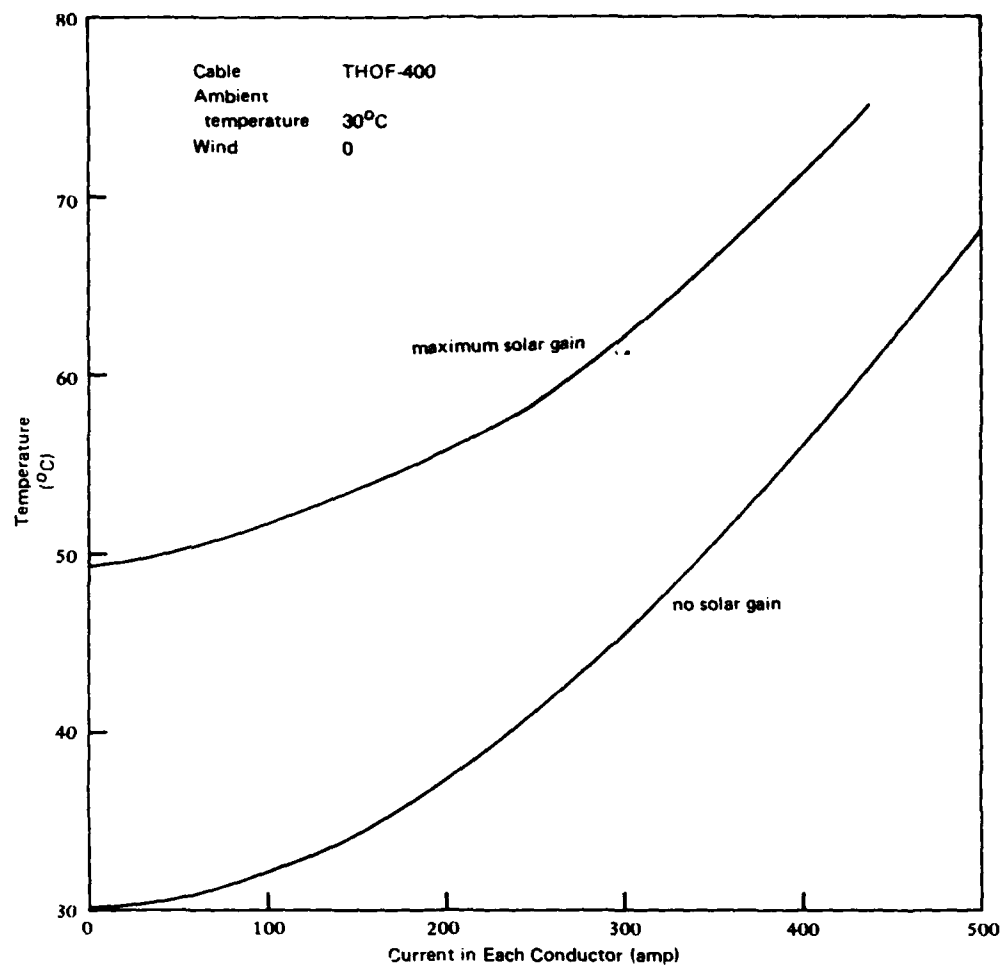


Figure 7. Maximum temperature of cable due to current and solar gain.

Appendix

AMPACITY CALCULATIONS FOR INSULATED ELECTRICAL CABLES

The ampacity of an insulated electrical cable in air can be calculated from the following formula [5].

$$I = \left[\frac{Q_c + Q_r - Q_s}{R} \right]^{1/2}$$

where I = current carried by the conductor
 R = resistance of the conductor in ohms per foot
 Q_c = heat transfer due to convection
 Q_r = heat transfer due to radiation
 Q_s = solar gain

For the case where there is no wind, the following equations may be used:

$$Q_c = 0.0803D^{0.75} [K_s - K_a]^{1.25}$$

$$Q_r = 0.124D \left[\left(\frac{K_s}{100} \right)^4 - \left(\frac{K_a}{100} \right)^4 \right]$$

where D = the diameter of the cable in inches
 K_s = temperature at the surface of the insulation in degrees Kelvin
 K_a = temperature of the air in degrees Kelvin

The solar gain is a function of the angle and the amount of sunlight that strikes the cable. The maximum solar gain at 43° N latitude is given by the formula

$$Q_s = 5.54D$$

This will change slightly with location but not with the ambient temperature.

The maximum temperature of the cable will be at the surface of the conductor. The temperature at this point can be calculated by the following formula

$$K_c = K_s + I^2 R \frac{4.21 \log \frac{D}{D_c}}{D_c}$$

where K_c = temperature at the conductor in degrees Kelvin
 D_c = diameter of the conductor in inches

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