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FIBER OPTICS IN THE "OPTIMUM" UNDERSEA ELECTRO_OPTICAL CABLE

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ABSTRACT

An evaluation is made of non-optical roles that optical fibers can play in improving the performance of deepsea tether cables. Here, "improvement" is defined in the context of compromises that must be made among conflicting system constraints during any search for a design which reduces cable diameter, while increasing cable power transmission and strength. The evaluation considers transferred power, cable length, voltage regulation, cable strength and cable diameter. Cables with 1-, 2- and 3 conductors are compared, at a common diameter of 17.3 mm (0.68") and a common length of 10 km. These parameters are compared for all three of the conductor options.

NOMENCLATURE

P Electrical power transferred by the cable (W), either to the cable end or to consumption points distributed along the cable length.

L Cable length (km).

V Supply voltage (VAC or VDC).

C A conductor's electrical conductivity (re 100% as the IACS standard for pure copper).

R Resistance of the tether circuit, including the sea if it is part of the circuit (ohm/km).

Ro Resistance of any seawater return (4 ohms here).

Rc Resistance of the cable's primary (i.e., center) conductor (ohm/km).

Rs Resistance of the shield conductor, if present (ohm/km).

Ko The system voltage regulation factor---defined here as the ratio of the load resistance to that of the tether circuit.

Kc In the coax cable, this is the ratio of center-conductor-to-shield resistances.

Vs Maximum allowed dielectric stress (1970 VDC/mm).

d Diameter of the cable's electro-optical core (mm).

D Final diameter of the armored cable (mm).

S The cable's ultimate strength (mm).

INTRODUCTION

Recent papers (1, 2) have studied the improved performance that optical fibers can provide in undersea electro-optical (E-O) cables, because they allow almost complete separation of the power- and telemetry roles. Reference (1) described the relative power-diameter-strength efficiencies of E-O cables using 1-, 2 and 3 electrical conductors. Reference (2) continued this analysis, and recommended two completely different design approaches to deepsea E-O cables.

(a) For large deepsea payloads, it proposed a 17.3-mm-diameter, 3-conductor, 3-phase, 3-fiber cable. This design might replace today's 17.3-mm armored coax, which has a limited telemetry bandwidth.

(b) For smaller deepsea payloads, a 7.9-mm cable could be operated from a hydrographic winch. This cable has 1 (or more) optical fibers---contained in and protected by a metal tube. The tube also acts as the cable's single electrical conductor in a power circuit with a seawater return.

The theme of the previous two papers is extended here to consider E-O cables with more rigorously stated designs, and to an evaluation of the effects of voltage regulation on power, length, diameter and strength. The arena for this contest is a deepsea operation in which a given cable must supply power P at voltage regulation Ko through cable length L. Cable strength S must be as high as possible for a given cable diameter.

CABLE DESIGN OPTIONS

Figure (1) sketches three approaches to the design of a tether cable's E-O core. If these designs have the same core diameter, then their contrahelical steel armor structures should be almost identical. A switch from one design concept to another should require only minor adjustments of the armor wire helix angles to preserve stress-, torque- and rotation balance.

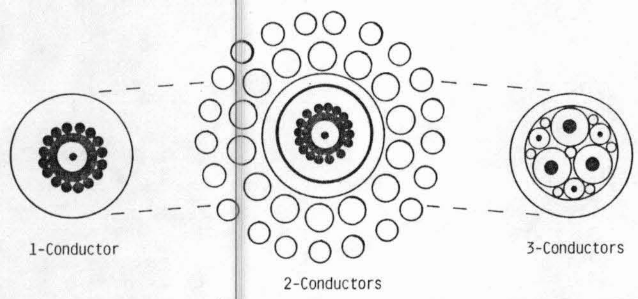

Fig. 1 Three conductor options for E-O tether.

ONE CONDUCTOR. Here, an elastic metal tube with moderate conductivity (e.g., C = 0.65) serves as the cable's only electrical conductor. A seawater circuit return is therefore needed. The tube encloses and contains the optical fiber(s) in a hermetically-sealed, very-low-stress environment. If lower resistance is needed to achieve maximum cable strength, a helix of copper wires can be served around the tube. Methods for such "optimization" of cable design are discussed in the next section.

Note that the single-conductor cable design has a symmetric cross section, and that only one layer of electrical insulation is required. This efficient use of cross section makes the cable core much smaller for given values of power transfer, voltage regulation and cable length. This, in turn, will increase the cable's strength for a fixed diameter. When cable strength and diameter are both critical, the single-conductor design approach should be given serious consideration.

In the single-conductor design, the relationships among (shipboard) supply voltage V, cable resistance Rc, seawater return resistance Ro, load resistance Rp, voltage regulation factor Ko, delivered power P and cable length L can be expressed as:

$$R \;=\; ((V^2 \cdot Ko/P/(1 + Ko)^2)/L \qquad \text{ohm/km} \qquad (1)^*$$

$$\;=\; Rc + Ro/L \qquad \text{ohm/km} \qquad (2)$$

where,

$$Ko \;+\; Rp/(Rc \cdot L + Ro) \qquad (3)$$

Usually, Ro/L is a small fraction of Rc. Here, Ro is assigned a value of 4, corresponding to a sea return through an infinite ocean. Voltage regulation factor Ko is typically varied between limits of 1 and 10. If its value is 1, then only 50% of the system's voltage drop occurs in the system electronics. When Ko is 9, that fraction grows to 90%.

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* For convenience, equations are shown in the form in which they might be used in a computer program.

For given values of P, L and D, maximum strength will be attained when Ko is equal to 1---that is, when one-half of total power pumped into the cable is dissipated in the tether circuit. This condition may or may not be desirable from the viewpoint of cable heating, power consumption or system electronic noise.

TWO CONDUCTORS (COAX). This design approach can be useful if a cable circuit return is required---for example, in a tether used in fresh water, or when the cable must be dipped into the water from a helicopter. Here, the center conductor is geometrically identical to the one in the 1-conductor design. But now, a second conductor is served around the primary insulation, and a second protective layer (the core jacket) is needed. In this design, symmetry of the cable cross section is preserved, but the additional conductor and insulation trespass into an annulus that could have been part of the loadbearing armor. Evaluation equations become;

$$R \;=\; ((V^2 \cdot Ko/P/L/(1 + Ko)^2)/L \qquad \text{ohm/km} \qquad (4)$$

$$\;=\; Rc + Rs \qquad \text{ohm/km} \qquad (5)$$

with,

$$Kc \;=\; Rc/Rs \qquad (6)$$

THREE CONDUCTORS. This design is based on the classic 3-phase power cable. Now, 3 optical fibers occupy low-stress positions in the helical channels defined by the electrical conductors. Normally, these fibers are overbuffered---i.e., given an additional jacket---and experience a near-hydrostatic environment when the cable is subjected to tensile-, bending- and flexural stresses. This can reduce or even eliminate fiber microbending, which is often the cause of severe excess optical attenuation.

A primary advantage for the 3-conductor design is that its helical core structure provides strain relief for the optical fibers when the cable is subjected to high tensile stress. But its low packing efficiency is a serious weakness. Note that a double jacket is now needed---one for each conductor and one for the core assembly. Also, considerable core space is occupied only by inert filler rods. (This inefficiency can be mortal for small E-O cables. It is much less serious for the 17.3-mm cables considered in this paper.)

The 3-conductor cable can be operated as a 3-phase AC circuit. It can also (more efficiently) support a DC power circuit, with conductors operated in parallel and with a seawater return. In either mode, the total resistance of each conductor will be;

$$R \;=\; 3V^2 \cdot Ko/P/L/(1 + Ko)^2 \qquad \text{ohm/km} \qquad (7)$$

with,

$$Ko \;=\; Rp/R \qquad (8)$$

In Equation (7), the supply voltage can be interchangeably DC or RMS. The numerical factor "3" appears because one-third of total power P will be transferred through each conductor. Decreased cable efficiency in 3-phase operations occurs because the corresponding peak values of the AC voltage cause much greater stress in the primary insulation. For a fixed constraint on voltage stress, that insulation must be correspondingly thicker.

DESIGN OPTIMIZATION

In most E-O cable designs, the system parameters P, L, Ko and D are imposed by non-cable constraints. The design task becomes one of searching for a cable configuration which will satisfy these constraints at a highest-possible value of cable strength.* This is best done by adjusting supply voltage V until a value has been found which satisfies that criterion. The associated analysis steps are outlined below.

(1) Select system values for P, L, Ko and D.
(2) Select an initial value for V, then use Equation (1), (4) or (7) to calculate the tether electrical resistance necessary to satisfy the P-L-Ko system constraints.
(3) Using resistance-ratio parameter Kc (if the cable is a coax), plus independent data on the conductor material and geometry, design a conductor with the required resistance value. (A computer program will do this automatically by imposing standard rules of geometry and material properties.)
(4) Calculate the insulation thickness needed to apply voltage V to the conductor with a voltage stress no greater than Vs. This defines the diameter of the jacketed conductor.
(5) If the cable is a coax, define a second conductor with resistance sufficient to reconcile R and Rc. For the 3-phase design, use standard geometry to calculate growth of the E-O core as the conductors are served together in a helix and wrapped with a binding tape.
(6) For the 2- and 3-conductor cable designs, add an insulating and/or protecting jacket. This will complete the initial design of the E-O core.
(7) Add the loadbearing armor---again to a standard set of geometry and material rules. Calculate the cable's weight, strength, strength-to-weight, etc.
(8) Add a voltage increment to V, then repeat design steps (2) through (7).
(9) For some value of V, the performance parameter selected will become optimum. If other constraints are acceptable, this V-value will serve as the basis for fine tuning the cable design.

In the E-O cable analyses to be presented here, in-common values have been assigned to a number of non-critical cable parameters---such as material strengths, helix geometries and electrical conductivities. Three of these constraints are important enough to emphasize.

#1 In addition to the thickness set by voltage stress constraint Vs, the center conductor insulations in the 1- and 2-conductor designs must have a minimum thickness of 1 mm. This constraint is added as a hedge against electrical shorts and pinholes.
#2 The minimum thickness for the primary insulation around the 3-phase conductors is 0.75 mm.
#3 A minimum thickness of 1 mm is required for all core jackets used in the 2- and 3-conductor cable designs.

Diameter responses to supply voltage variations are shown in Figure (2) for the single-conductor E-O cable. Note that the conductor's diameter continues to decrease after the dielectric jacket has reached its minimum value and started to increase again. For this design, the cable's maximum strength was achieved at a voltage of 1500 VDC.

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* "Optimization" might also be defined in terms of maximum strength/weight ratio ("free" length), or even as a minimum diameter for a given strength.

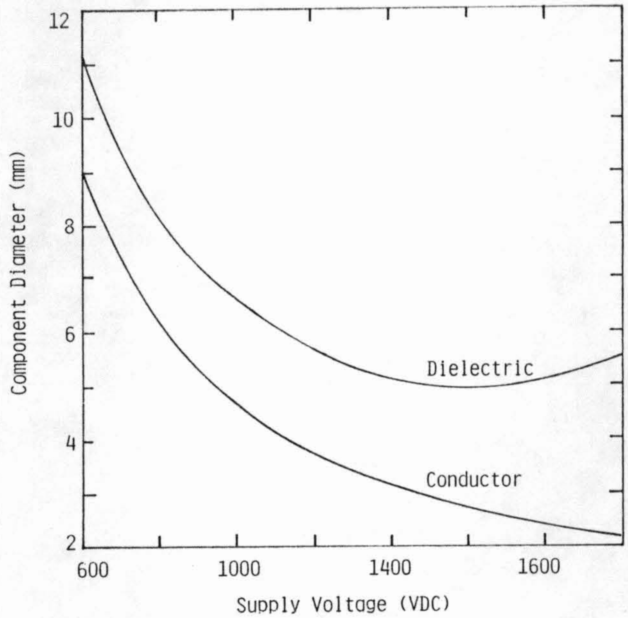

Fig. 2 ONE CONDUCTOR: Effects of voltage V on component diameters when P = 10 kW, L = 10 km and Ko = 1.

Figure (3) shows the effects of supply voltage on component diameters for the two-conductor E-O cable. System performance constraints are the same as for the one-conductor design, and the center conductor accounts for 75% of the cable's loop resistance (Ko = 0.75).

Note in Figure (3) that minimum diameter occurs at a lower voltage for the primary insulation than it does for the jacket. This is because the 2nd conductor's resistance continues to increase as V increases. The O.D. of the 2nd conductor will therefore become minimum at a somewhat higher value of supply voltage.

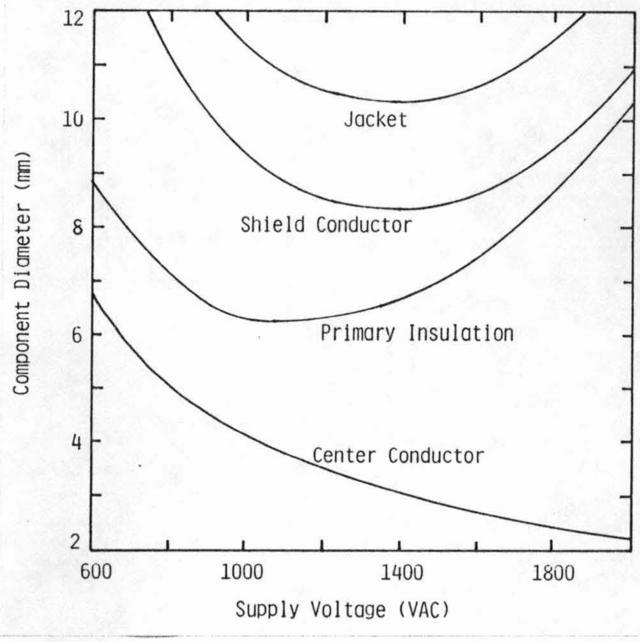

Fig. 3 TWO CONDUCTORS: Effects of voltage V on component diameters when P = 10 kW, L = 10 km and Ko = 1.

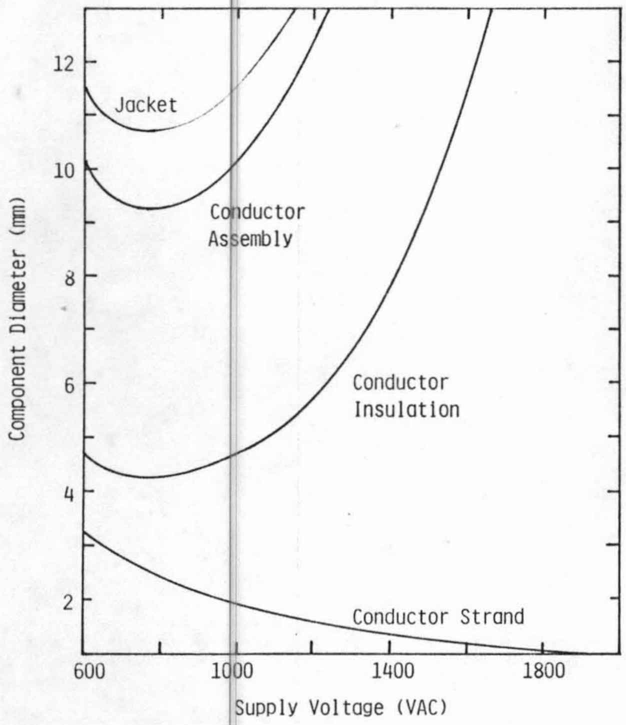

Fig. 4 THREE CONDUCTORS: Effects of voltage V on component diameters when P = 10 kW, L = 10 km and Ko = 1.

Figure (4) shows how the components in the 3-phase E-O cable respond to changes of supply voltage. Note the enormous diameter increase that must occur when the three jacketed conductors are assembled as a conductor helix. This phenomenon, plus the large amount of inert or filler space shown for the 3-conductor cable unit in Figure (1), demonstrates the functional inefficiency of the E-O section in this type of cable.

COMPARISON. The different performances of these three E-O core types are summarized below for a common cable diameter of 17.27 mm. It must be remembered that system constraints on power, length and regulation are identical for all three. Their different responses constitute a fundamental statement regarding relative power/strength/diameter efficiencies. Of course, cable flexibility and fiber strain relief must also be part of any design tradeoff.

E-O Core Type	1-COND-DC	COAX-AC	3-PHASE
Optimum Voltage	1502 VDC	1332 VAC	732 VAC
Minimum O.D.	4.9 mm	10.4 mm	10.7 mm
Strength	320 kN	232 kN	220 kN

The performance of the E-O coax cable was based on a conductor resistance ratio of Kc = 0.75. If more of this resistance is shifted to the 2nd conductor (say, Kc = 0.5), then that cable's performance is altered---to a 9.9-mm-diameter core at 1350 VAC, with a strength of 240 kN. This change will reduce the flexibility of the center conductor, and may affect operating life.

DESIGN SENSITIVITIES TO POWER AND VOLTAGE REGULATION

In Equations (1), (4) and (7), transmitted power P and cable length L appear (almost) always as a pure P-L product*. In fact---with the footnoted caveat---any statement of this product is sufficient to define a cable's optimum operating voltage, minimum E-O core diameter and maximum strength. Within this constraint, we are free to adjust P or L. If we do so, then line current will change, but not the cable structure.

Figure (5) plots optimum power-length-strength responses for the three E-O core types in Figure (1). All designs are based on a 17.27-mm armor diameter, and all use the same component materials---e.g., the same metals, tensile strengths and conductivities.

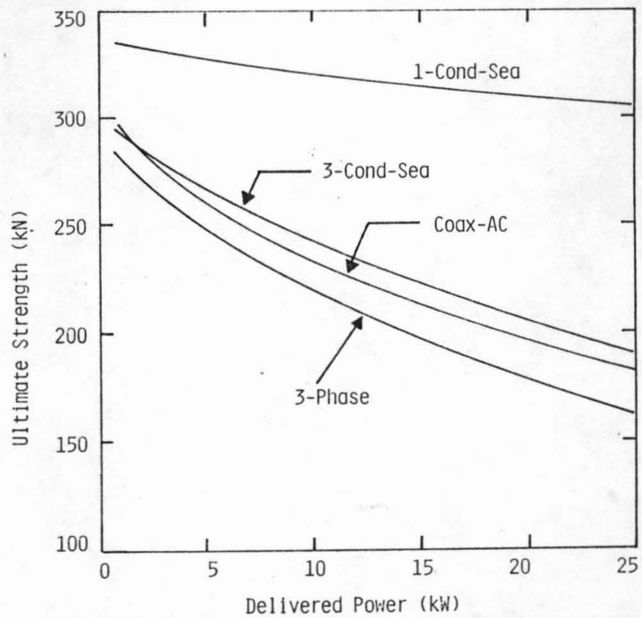

Fig. 5 Relationships of strength to power for L = 10 km, D = 17.27 mm and Ko = 1.

Note that Figure (5) describes four cables. The fourth one is the 3-phase design already described, but now operated DC, with all 3 conductors in parallel and a seawater circuit return. Its strength advantage over the "3-Phase" design is obtained because the reduced stress allowed with DC permits the jacketed conductors to have a smaller diameter. This allows more annulus to be dedicated to the loadbearing armor.

The simplicity and symmetry of the 1-conductor E-O cable provides a major strength contribution at all P-L product values. This advantage increases at high power levels, and points clearly to two applications for this type of cable.

(1) At any diameter, when the cable must transfer high power levels through a considerable length (i.e., when P-L is very large).
(2) At any P-L value, when the E-O cable must be as small as possible. This is especially true for cables which must operate from a hydrographic winch with diameters less than about 8 mm.

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* This statement is not quite true in Equation (1), where Ro is a small but finite part of the total tether circuit resistance. For typical values of Rc-L, the 4-ohm value of the seawater return will be almost negligible.

Relationships between cable strength and voltage regulation are plotted in Figure (6) for P = 10 kW and L = 10 km. All data points in the figure represent cables with optimum (maximum) strength for the design conditions shown. In all four examples, cable strength is greatest when Ko is equal to one---that is, when one-half of V and P are dissipated in the cable.

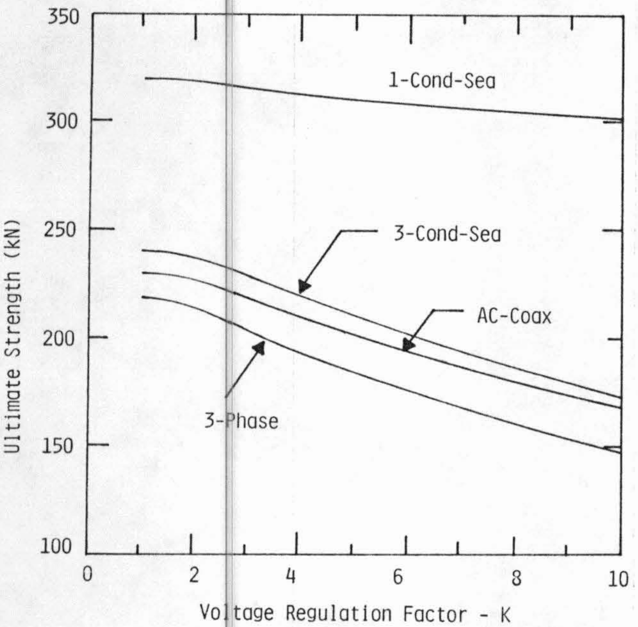

Fig. 6 Relationships of strength to voltage regulation when P = 10 kW, L = 10 km and D = 17.27 mm.

Again, notice that the single-conductor E-O cable has both higher strength and much less loss of that strength at high values of Ko.

CONCLUSIONS

The single-conductor E-O cable, operated DC with a seawater return, should be an excellent candidate for use in ocean tether systems where cable diameter limits are a serious constraint on both strength and power transfer.

The 3-conductor E-O cable---operated as a 3-phase system or DC with seawater return---is a viable choice in larger cables, and where the optical fibers must be given appreciable strain relief. Of all the designs evaluated here, the 3-phase cable has the least power-to-strength efficiency.

The E-O coax cable can be operated in either AC or DC modes. In either format, it offers no special advantages where power or strength are concerned. The best application for this cable may be in situations where cable power return is essential, and where the special protection offered to the optical fiber(s) by the metal tube conductor is also needed.

What about the physical limits of seawater circuit returns? The author can only quote his earlier note from Reference (1).

> "What are the physical limits to the seawater circuit return? European experience is a helpful gauge here...the Skagerrak Sea power cable runs more than 130 km between Norway and Denmark, delivering 250 megawatts at a 1000-ampere DC current (3). Until a second cable was installed in the late 1970's, this power transfer was accomplished with a sea-water return across the Skagerrak. Only 2- to 3 km offshore, current densities were below the threshold of detection."

REFERENCES

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