HOW SMALL CAN AN ELECTRO-OPTICAL TRANSOCEANIC CABLE BE?

George A. Wilkins
Environmental Sciences Department
Naval Ocean Systems Center
Hawaii Laboratory
Box 997
Kailua, Hawaii 96734

ABSTRACT

Design theory and analyses are presented for a transoceanic, electro-optical (E-O), telemetry cable which---because its data, power and tensile functions can be separately optimized---has a very small diameter and transport volume. These reductions are achieved with no compromises of operational or material constraints on the telemetry system. For example, an ocean E-O cable which can directly support repeatered, multi-fiber telemetry between Japan and the United States will have a diameter less than 0.75 cm. Its transport volume will be barely 5% of that required for the smallest coaxial cable (SD List 1 with a 3.18-cm diameter) now being used in transoceanic communications.

A cable design is demonstrated for a set of system parameters which define a 5550-km-long “baseline” communications system. The study evaluates that system’s sensitivity to changes in such system parameters as length, repeater power and separation, water depth and safety factor, cable specific gravity, dielectric voltage stress, conductor conductivity, and the failure- or yield strains of loadbearing components. It is concluded that the cable should be relatively inexpensive. Its design can be tailored for specific applications with little change in manufacturing complexity or cost. The cost and risk of ocean deployment should be considerably reduced, since small ships can be loaded with ocean-crossing lengths of this miniature E-O cable.

INTRODUCTION

Another paper in these Proceedings (1) has described the enormous bandwidth increases that optical fiber technology can offer to undersea communications. Telemetry at 274 megabits/second/fiber becomes reasonable; and the cable’s total bandwidth can be several gigabits/second.

But bandwidth is only one of the revolutionary changes that can be triggered in undersea communications by fiber optics technology. This paper examines the issue from a totally different perspective---the role of fiber optics in reducing the diameter and transportation volume of the transoceanic (or “long haul”) telemetry cable.

The primary design objective was to create, characterize and evaluate an undersea E-O cable whose diameter was as small as it could be. The principal design constraint was that no compromise of system specifications would be allowed. The resolution of such goals under such constraints is difficult at best, and it is only fair that the study rationale and premises be stated.

(1) Fullest possible advantage was taken of the fact that---unlike a coaxial cable---the E-O cable’s power and data functions can be separated, and can then be separately optimized. To a somewhat lesser extent, this is also true for the loadbearing function in the cable.

(2) New materials were evaluated for use in the E-O cable, and hybrid roles were sought for each component. Examples of the first kind include the use of new copper alloys and of DuPont’s KEVLAR-49 (2). Examples of the second approach include KEVLAR’s simultaneous use as the primary tensile structure and as an armor for the cable’s electrical section.

(3) The optical fibers were exposed to selected environmental stresses, such as tensile strain and deep ocean hydrostatic pressure. But fiber strain was allowed only to the relatively low yield strain limit of the metal conductor. Deep submergence pressure was allowed because (though enormous) it is still quite low compared to the radial pressures that can be imposed on an optical fiber by an external armor helix. Our laboratory has shown (3) that a well-buffered optical fiber will respond to armor “squeeze” with very low or even negative excess optical attenuation. The key design constraint that must be considered here is the need for quality control in the fiber’s elastomeric buffer(s). These protective elements must be essentially free of defects. (A typical buffer defect has spatial dimensions comparable to the spatial periods of the fiber’s most loosely bound propagation modes. This increases the probability of resonance scattering losses due to microbending of the optical fiber around these defects.)

(4) Cable cross-sectional geometry was kept concentric and coaxial. While this does not necessarily reduce cable diameter, it does simplify design responses to changes in system operating parameters. It can also result in reduced manufacturing costs through lower capital investments for cabling machines, and through greater machine versatility.

Above all else, the design technique emphasized synergism; as cable functions and components were required to interact along a path leading toward reduced cable diameter. For example, the use of lightweight KEVLAR-49 as the primary loadbearing element and armor allowed a sharp decrease in the in-water weight of the cable. A part of this weight saving was invested in the electrical conductor, whose diameter growth allowed a reduction of system voltage and less thickness for the dielectric insulator. These interactions allowed more design freedom in balancing a conflict between simultaneous needs for higher safety factor (higher strength/weight ratio) and higher specific gravity (less response to near-bottom ocean currents).

CABLE GEOMETRY

While the E-O cable's cross section (Figure 1) is similar to that of another patented ocean cable (4), it has a number of basic structural differences. The most important of these is the use of a lightweight loadbearing armor, rather than steel wires. The design and analytical freedoms allowed by this change have already been described.

Note that the cable has a single electrical conductor, since it is designed for use with a seawater power return. When the cable is used in transoceanic communications, it will most likely be powered from both ends and a ground plane will be located at a cable midpoint. If the E-O cable is to support an offshore experient, then the ground plane will be located at the seaward end of the power/data link.

Although the wall of the electrical conductor is sufficiently thick to serve as a deep ocean pressure hull, it is not assigned such a role. In fact, the tubular conductor is filled with a non-setting gel which transmits full sea pressure (as a hydrostatic force) to the optical fiber(s).

The Optical Cavity

This axial cable section serves as a protective enclosure for the optical fibers. It contains 1 to 6 fibers; depending on telemetry requirements, on the diameter of each fiber's buffer jacket, and on the cavity diameter. In addition to its role in transmitting hydrostatic forces, the void filler will lubricate the fiber jackets to prevent "stiction" and microbending.

The E-O cable design does not restrict the choice of optical fibers, which can be step index, graded index, multi mode or single mode units. They can even be a mix-and-match of these. The fibers must, however, show little or no response to hydrostatic pressure. They must also survive the moderate tensile strain (less than about 0.2%) caused by cable-laying stresses.

The Electrical Conductor

This tubular element is formed (see Figure 2) by the rolling of a flat-tape stock of tempered copper alloy. Just before tube closure, the optical fibers are inserted, and the void filling gel is flowed into the central channel. Finally, the tube is pressed shut and the closure seam is permanently welded or soldered. The tube's inner- and outer diameters are, respectively, D2 and D3. Wall thickness T is described by the shape parameter,

$$K = T/D3 \tag{1}$$

This parameter has a maximum value of 0.50 for a solid rod. It serves as a critical measure of the extent to which the tape must be circumferentially yielded without buckling as the conductor tube is being formed.

The Dielectric Annulus

This structure (O.D. = D4) will be a conventional extrusion of a conventional elastomer such as high density polyethylene. The only unusual manufacturing constraint might be a requirement that the metal conductor must be stored on a reel with a relatively large core (diameter ratio > 200) to ensure that it is not yielded during handling, and that it remains straight and concentric during transit through the dielectric extruder head.

Note that the dielectric has only an insulation role. Unlike the dielectric spacer in a coaxial cable, it plays no part in telemetry for the E-O cable. This means that specifications on the quality, circularity, concentricity and surface finish can be somewhat relaxed. For example, the extruded dielectric need not be passed through a shaving head.

The Loadbearing Armor

This annulus is constructed of multiple filaments of KEVLAR-49, locked within a void-free matrix of thermosetting epoxy. It has two critical functions in the cable. First, it must serve as the primary loadbearing element, although some fraction of the tensile load will always be carried by the electrical conductor. Second, the annulus will function as an armor---as an abrasion- and penetration-resistant layer which completely covers and protects the E-O cable's electrical section. This second role is a natural one for KEVLAR, since the material is widely used in ballistic armor composite structures.

The KEVLAR-49 is assumed to occupy 56.5% of the loadbearing annulus. This is a match with past experience (3) in similar structural uses of the material. For torque balance and to improve flexibility, the filaments are served into the cable as a contrahelix. In all designs analyzed here, the longest helix length allowed is 25-times the outer diameter (D5) of the loadbearing armor. This is a compromise between the conflicting requirements for flexibility and high tensile modulus in the cable. It defines a maximum helix angle of,

$$\emptyset = \mathrm{Tan}^{-1}(\pi/25) = 7.2^\circ \quad (2)$$

Outer Jacket

In the final manufacturing step, a thick tough jacket is extruded over the loadbearing structure. This jacket, probably a black polyurethane, serves as a barrier against water intrusion. It also defocuses external abrading or cutting forces. In the designs discussed here, the cable's overall diameter has arbitrarily been assigned the value,

$$D6 = D5 + 1.50 \text{ mm} \quad (3)$$

CABLE DESIGN THEORY

Table (1) defines a set of "baseline" operational and material constraints which have been used to initiate this design study. The table also shows the range of values over which parameter sensitivity analyses have been carried out. These parameters can define either a transoceanic communications cable or a power/data cable used to support a midocean experimental array. Earlier thoughts by the author on these subjects can be found in (5) and (6).

	Operating Or Material Parameter	Baseline Value	Range Of Values
L	Cable length (to sea ground) (km)	5550	1000---20,000
---	Ocean depth (km)	7	Fixed
F	Deployment safety factor	2	1.0--------10
Σ	Cable specific gravity	$\geq$ 1.50	-----
Δ	Repeater separation (km)	50	10--------250
P_R	Per-repeater power (watts)	0.50	0.1-------2.5
P_L	Power to end of cable (watts)	45	0---------450
C_R	Conductor conductivity (re IACS)	0.95	0.20-----1.02
V_s	Allowed dielectric stress (VDC/mm)	3940	1970-----5910
σ_y	Conductor yield strain	0.0034	0.001---0.010
K	Conductor shape parameter	0.15	0.03-----0.50
S_K	Ultimate stress for KEVLAR-49 (at its 2.5% ultimate strain (kg/cm^2)	28,120	Fixed

Table (1). Parameter Values Used In E-O Cable Analysis

For example, the 5550-km length of the baseline design is easily enough for a repeatered E-O cable run from San Francisco to Tokyo (assuming that a power return is used from mid-ocean). It would allow a telemetry cable from Land's End, England to Land's End, Rhode Island without such a ground plane.

Design Of The Electrical Section

The E-O cable is powered by an onshore voltage V (DC volts), which drives a line current I (amps) through the resistances of the cable (R_c), the seawater return (R_s), the repeaters (each R_R), and (if used) the end load (R_L). The resistance of seawater is so low that it will be ignored here. The cable contains "N" repeaters, where,

$$N = (L/\Delta - 1) \quad (4)$$

This study will also ignore end-to-end differences in earth-ground voltages, since these will be quite route specific. (Such differences can be treated in terms of either an arbitrary additional value for P_L or for V.) Supply voltage V will be;

$$V = I\left[R_c \cdot L + R_L + (L/\Delta - 1)R_R\right]$$

$$= I\left[R_c \cdot L + \frac{P_L + (L/\Delta - 1)P_R}{I^2}\right] \text{ VDC} \quad (5)$$

It is convenient here to define a parameter "P", equal to the power consumed by all offshore elements of the telemetry system except for the conductor and the seawater return.

$$P = P_L + (L/\Delta - 1)P_R \quad \text{watts} \quad (6)$$

so that,

$$V = I(R_c \cdot L + P/I^2) \quad \text{VDC} \quad (7)$$

and,

$$R_c = (V - P/I)/IL \quad \text{ohms/km} \quad (8)$$

Cable line resistance can also be expressed in terms of conductor dimensions and fundamental electrical parameters. In Equation (9) below, ρ is the material resistivity which corresponds to an (IACS) relative conductivity of 100%; i.e., to 1.724 microohm-cm.

$$R_c = \frac{\rho(10^5 \text{ cm/km})}{(\pi/4)(D3^2 - D2^2)} \qquad \text{ohm/km} \qquad (9)$$

or,

$$D3 = \sqrt{\frac{0.21952}{C_R \cdot R_c} + D2^2} \qquad \text{cm} \qquad (10)$$

Equation (10) is quite convenient for the cable designer, since it allows the inside diameter of the optical cavity to be fixed. The same equation drives the conductor manufacturer up the wall. Any design change that affects R_c must also change both D3 <u>and</u> the ratio of wall thickness to D3. The ratio K is a critical parameter to the tubing manufacturer, and measures the degree to which the conductor alloy must be circumferentially overstressed (yielded) as it is formed into a tubular cross section.

One convenient way to resolve the problem is to restate Equation (10) in terms of K, while allowing D2 to be a dependent variable of the design. In Equation (12) below, A_c is the conductor's cross-sectional area.

$$D2 = (1 - 2K)D3 \qquad \text{cm} \qquad (11)$$

$$A_c = \pi K(l - K)D3^2 \qquad \text{cm}^2 \qquad (12)$$

and,

$$D3 = \sqrt{\frac{0.05488}{C_R \cdot K(1 - K)R_c}} \qquad \text{cm} \qquad (13)$$

For a dielectric insulation applied uniformly and concentrically around the cylindrical conductor, the allowable voltage stress will be;

$$V_s = \frac{2V}{D3 \cdot \text{Ln}(D4/D3)} \qquad \text{VDC/cm} \qquad (14)$$

so that,

$$D4 = D3 \cdot \text{Exp}(2V/V_s \cdot D3) \qquad \text{cm} \qquad (15)$$

In solving Equations (6), (8), (13) and (15), we can analytically determine the dimensions of all components in the electro-optical section of the long haul cable. That solution is exact and (by juggling V and I) can give a precisely minimum value for D4.

Unfortunately, this value is also incorrect, since it does not consider the total spectrum of electrical and physical constraints on the cable design. The interim value for D4 ignores the effects of such parameters as specific gravity, deployment depth and safety factor. These will modify D2, D3 and D4---and some apparent design solutions may become forbidden.

Design Of The Physical Section

Both the armor and the conductor sections of the cable will contribute to its useful strength. Care must be taken, however, in defining "useful". In this paper, that term is determined by the tensile moduli of the loadbearing components, by their cross sections, and by the limiting values of a σ_i for some cable materials. For example:

$\sigma \leq \sigma_y$ This limits σ to 0.34%, the strain at which the tubular conductor yields (as defined by the normal criterion of 0.2% strain offset). A cable strain greater than σy will result in permanent elongation of the cable, as well as in changes in its electrical, physical and/or optical behavior.

$\sigma \leq 1.0\%$ This is the <u>minimum</u> proof strain to which the optical fiber will have been subjected. Within the confines of this new strain interval, we can be reasonably certain that the cable will withstand any short-term tensile stress without an optical fiber failure. The metal conductor will be permanently stretched, and there is danger that---near the upper limit of this strain interval---the conductor may fail.

$\sigma \leq 2.5\%$ The upper limit here represents the ultimate strain for KEVLAR-49. Short of this limit, the E-O cable will have an extremely linear stress/strain behavior. The 2.5% strain level, therefore, represents the E-O cable's physical survival strength. At that strain level, all optical fibers and (probably) the electrical conductor will already have failed.

In the analyses reported here, "useful" cable strength S_y corresponds to an axial strain of σ_y---the conductor yield strain and the highest recoverable strain. A safety factor F = 2 means that the normal working load is just one-half of S_y. The conductor's tensile modulus $E_c = 1{,}195{,}000$ kg/cm^2 for $\sigma \leq \sigma_y$, and is assumed to be zero above that strain level. Within the load-bearing armor, the fractional area occupied by KEVLAR-49 filaments is 56.5%. At relative tensile strain a σ_y cable loading becomes;

$$S_y = \pi\sigma_y \left[E_c \cdot K(1 - K)D3^2 + \frac{0.565}{4(0.025)}(D5^2 - D4^2)S_K \right]$$

$$= \pi\sigma_y \left[E_c \cdot K(1 - K)D3^2 + 5.65(D5^2 - D4^2)S_K \right] \text{ kg} \qquad (16)$$

Note the direct and linear impact that an increase in σ_y will have on the E-O cable's useful strength. For very higher tensile loadings, that part of the KEVLAR-49 strength which is excluded from Equation (16)---about 85%---can be tapped. The dire effects of such a loading on the cable's electrical and optical integrity have already been pointed out.

In-water weight can be obtained by summing weights over all cable components, including the displaced seawater. (Seawater is assumed here to have a deep-ocean specific gravity of 1.04.)

$$W_w = 100 \left[\sum \Sigma_i \cdot A_i - \frac{1.04\pi}{4}(D6)^2 \right] \text{ kg/km} \qquad (17)$$

and the cable's specific gravity will be,

$$\Sigma = \frac{W_w}{25\pi(D6)^2} + 1.04 \qquad (18)$$

Design Procedure

The following procedure should be followed during design of the long haul E-O cable described in Figure (1) and Table (1).

(1) Fix the "invariant" system parameters; e.g., the material properties, D2 (or K), jacket thickness and the KEVLAR-49 armor fraction.

(2) Select the applicable system parameters---water depth, L, P_L , P_R, Δ and Σ (as $\Sigma \geq \Sigma_{min}$). Then solve:

(a) Equation (6) to obtain P.

(b) Equation (8) for R_c.

(c) Equation (10) or (13) for D3.

(d) Equation (15) for D4.

(3) Optimization of the E-O cable design will then consist of finding that minimum value of,

$$D6(V,I,D5) = D5 + 1.5 \text{ mm} \quad (19)$$

which satisfies all of the constraints in Table (1). Parameters V, I and D5 will be the independent variables in this search. All three must be adjusted until, using Equations (16) through (18), the least value of D6 is found which satisfies:

$$F = S_y /(W_w \cdot \text{depth}) \quad \geq 2.0 \quad (20)$$

$$\Sigma \geq \Sigma_{min} \quad = 1.5 \quad (21)$$

and,

$$D5 - D4 \quad > 0 \quad (22)$$

The product of safety factor F and water depth is sometimes referred to as the cable's free length---that cable length whose in-water weight is equal to its strength when hanging over the side into an arbitrarily-deep ocean.

The constraint of Equation (22) is added as a reminder that the annulus of KEVLAR-49 has two critical roles. Even if it were not needed for strength, this structure is still essential as an armor for the electrical section. It must not be allowed to disappear from the cable.

Relationships Of V and I To P

Voltage drops and resistance values for the E-O repeaters and end load can be calculated via the normal relationships among V, I, R and P. For any value of V and I, system power levels will be related by the expression,

$$V \cdot I = P_c + P \text{ (watts)} \quad (23)$$

where P_c is the power dissipated in cable resistance. In addition---at that unique set of values for V, I and D5 which results in a minimum for D6---the product of supply voltage and line current will normally satisfy the special relationship,

$$V \cdot I = 2P \text{ (watts)} \quad (24)$$

While Equation (24) is offered here only as an empirical relationship, it can be remarkably precise---on the order of 1 part in 10,000. This precision is true only for supply voltages less than about 125% of the value which makes D6 a minimum, and for cable specific gravity higher than about 1.25. Outside these limits, Equation (24) can break down rather badly.

In special designs where I is fixed and V and D5 are varied, Equation (24) is usually not correct. If the validity of this relationship is in doubt, test the solution D6 = D6(V,I,D5) at higher and lower values of current. For Equation (24) to be true, both of these adjustments must cause the deployment safety factor to decrease.

If constraints on the design of the long haul E-O cable were only electrical, then the rationale for Equation (24) would be clear. But they are not; in fact, these constraints form a very mixed bag of electrical and mechanical design specifications. It is probable that electrical constraints on the E-O data link are so dominant that Equation (24) simply shows the design impact of matching the line to the load. Until a theoretical understanding can be offered, Equation (24) must be regarded as (only) a fortuitous empirical relationship.

THE “BASELINE” CABLE DESIGN

This design theory is sufficient to support the optimization of the E-O cable, The procedure is so direct that it has been programmed on an HP-97 printing calculator. Given a set of system constraints, such as those in Table (1), a printout of design parameters and performance levels can be obtained in less than 15 minutes. (This record has often been matched on an airplane, while simultaneously balancing a drink, in bumpy weather.)

Table (2) summarizes the design and performance of the “baseline” E-O cable; i.e., that least-diameter design which satisfies Table (1) constraints on the data link.

Note that the ultimate strength S_u is more than 5-times greater than the “usable” strength S_y. This is testimony to the improvements that can be gained if the yield strain of the conductor can be increased.

In Table (2), the cable design is defined for a unique value of the supply voltage. As Figure (3) shows, this voltage corresponds to a minimum value of D6. Actually, the D6 curve in Figure (3) presents a family of minimum-value solutions to the cable design. All points on that curve satisfy the set of system requirements in Table (1). But only <u>one</u> point, the one described in Table (2),represents a double-minimum value.

Parameter		Value
V	Voltage (VDC)	3855
I	Current (amp)	0.0519
R_c	Resistance (Ω/km)	6.682
D2	Conductor I.D. (mm)	1.82
D3	Conductor O.D. (mm)	2.60
T	Wall thickness (mm)	0.39
D4	Dielectric O.D. (mm)	5.52
D5	Armor O.D. (mm)	6.66
D6	Cable O.D. (mm)	8.16
S_y	Load at σ_y (kg)	347.
S_u	Load at failure of KEVLAR-49 (kg)	1846.
W_w	In-water weight (kg/km)	24.8
Σ	Cable specific gravity	1.513

Table (2). Baseline Cable Design.

At supply voltages lower than the optimum value, the need for a higher line current increases cross sectional areas for both the conductor (reduced line resistance) and the armor (greater strength to carry the increased in-water weight). The result is that the cable's diameter increases---very steeply if V is appreciably less than its optimum value.

At higher supply voltages, the conductor will shrink. But now the constraint on voltage stress forces the thickness of the dielectric to grow. Again, the cable's diameter must become larger. At the same time, the combination of less metal and more dielectric decreases the cable's specific gravity to the point that it fails the $\Sigma \geq 1.50$ constraint. Therefore, the right side of Figure (3) represents a "forbidden" design region. (Note also the thinning of the armor annulus in this region.)

Figure (3) shows that the conductor's diameter will also begin to grow at high values of supply voltage. With the onset of this behavior, the V-I-P relationship in Equation (24) begins to fail. All component diameters shown for these high voltages are still precise and accurate---it is just that they can no longer be calculated accurately via Equation (24). The more general form in Equation (23) remains valid, but minimum values of D6 must be found by independently adjusting V, D5 and I.

CABLE DESIGN SENSITIVITY

The sensitivity of D6 to changes in system parameters has been evaluated for all of the operational and material constraints listed in Table (1). As was the case for D6(V), only one parameter at a time was allowed to change. Each solution represents the minimum value that D6 can have, given that particular set of constraints.

Figures (4) through (12) illustrate those variations of component diameters which result when L, F, Δ, P_R, P, C_R, σ_y, K and V_s are individually varied. In each case, the solid black circle corresponds to the baseline conditions of Table (1), and dashed-line entries mean that $\Sigma \leq 1.50$.

Figure (4) should be interpreted with some care. As Equation (6) shows, any change in L (which is not balanced by changes in Δ and P_R) must also change system electronic power P. This means that two parameters have been changed in Equation (8). The Figure actually says that "System length L was changed without changing P_L, P_R or Δ. Therefore, P will become greater, and P_c must increase (per Equ. 24) to balance this change."

Two very important conclusions should be apparent from close study of Figures (3) through (12). First, variations of D6 are relatively mild in the face of quite large changes in system constraints. Second, the relationships among internal cable components remain reasonable for these same parameter changes. Both of these conclusions support the greater conclusion that the E-O cable can (a) be fabricated at relatively low cost, and (b) tailored for specific applications at similarly low costs (in time, dollars or complexity).

Figure (13) is offered with some trepidation, since it violates all rules on the need for simplicity in data graphs. The complexity is not only necessary but helpful. Figure (13) shows---in one place---the relative sensitivity of the long haul E-O cable's diameter to all of the operational and material constraints listed in Table (1). The slope of each curve in the Figure is a direct measure of the power-law relationship between that parameter and the diameter of the E-O cable.

The insensitivity of cable diameter to extreme variations of the system parameters can also be illustrated by noting that:

(1) In Figure (3), cable diameter appears to vary rather gently with supply voltage V. Large relative excursions from the baseline value of V are needed before the slope of the function D6(V) begins to steepen.

(2) Yet, as Figure (13) shows, the effect of V on D6 quite rapidly becomes the most sensitive relationship of all those studied.

Cable Tailoring Options

One realistic test of our assumption of generality for the E-O cable would be to determine its response to one or more “tailor made” perturbations of the telemetry system. Two such perturbations are considered here---tapering or reduction of cable diameter as a function of distance offshore, and adjustment of line current to some non-optimum value (e.g., to allow a matching of bias voltage with requirements of repeaters or end-load electronics).

Cable Tapering. While all constraints in Table (1) remain in force, we have the option of applying the voltage stress constraint over and over again as the cable moves offshore. Assume this is done periodically for the baseline E-O telemetry system. Assume also that the dimensions of the conductor tube are not changed (one of many tapering options). Figure (14) illustrates the results. No compromises have been made with any system constraint, but the reduction of total data link volume is nearly 30%.

Those manufacturing changes necessary to “tailor” the cable shown in Figure (14) will be quite simple. Generally, they consist of adjustments no more complicated than the periodic changing of extrusion die diameters.

Current Adjustment. The baseline cable design required a current of 51.9 mA. Assume that we need to adjust the design so that D6 is minimized when I is equal to 50 (or 100) mA. These currents will allow per-repeater power to be 0.50 watt at bias levels of 10 and 5 volts, respectively.

For I = 50 mA, cable diameter becomes 8.165 mm. This is less than a 0.02% increase in cable diameter. When I = 100 mA, D6 is 8.647 mm---a growth in diameter of slightly less than 6%. Total system electrical power is $V \cdot I$, or 194 watts at 50 mA and 383 watts at 100 mA. These levels should be compared to $V \cdot I = 2P = 200$ watts for the baseline design. Clearly the system does not satisfy Equation (24) at either new current value. Just as clearly, neither current adjustment demands large diameter (or performance) penalties.

CONCLUSIONS AND PLANS

Analyses reported here show that use of optical fibers in undersea telemetry cables can decrease the diameters of such cables by factors of at least four. Cable transportation volumes can be as little as 5% of those required for the smallest transoceanic coaxial cable (SD List 1) now in commercial use.

A design theory has been presented which can precisely determine E-O cable component diameters and data link performance---and which remains valid even if operational and material constraints are changed by more than an order of magnitude. A design is presented for a E-O data link which can run 5550 km (3000 n. miles) to an oceanic experiment or ocean power ground. The diameter of this cable is 8.16 mm. If the cable is shortened to about 4500 km, its diameter will be less than 7.5 mm. This shorter cable, powered from both ends, could support optical telemetry between Tokyo and San Francisco, and could be deployed as a single load from one of the smallest U.S. cable ships.

This E-O cable should be much easier to fabricate and less expensive than a conventional ocean coaxial cable. This conclusion is being tested in a Navy cable development program---fabrication of a 1-km prototype E-O cable, as described in Table (2). Industrial participants include:

ITT-EOPD (Roanoke, VA) will supply the optical fiber (at no cost to the government) to Olin Corporation for insertion into the metal conductor.

Olin Corporation (New Haven CT), also at no cost to the government, is developing the technique for forming of the conductor tube, insertion of the optical fiber(s) and void filler, then closing and welding the tube. A 1-km length of such an E-O tube will be supplied to Air Logistics (see below).

Air Logistics Corporation (Pasadena, CA) is working under Navy contract to assemble the remainder of the cable structure. Extrusion of the dielectric and jacket will be subcontracted to South Bay Cable (Idyllwild, CA).

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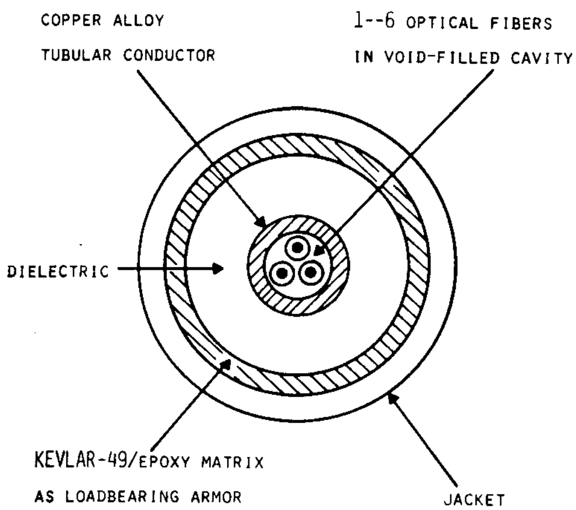

Figure (1)
Geometry Of E-O Cable

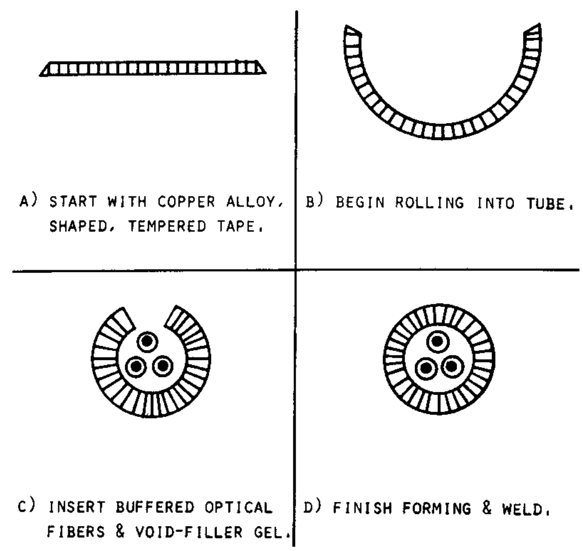

Figure (2)
Assembly Of E-O Conductor

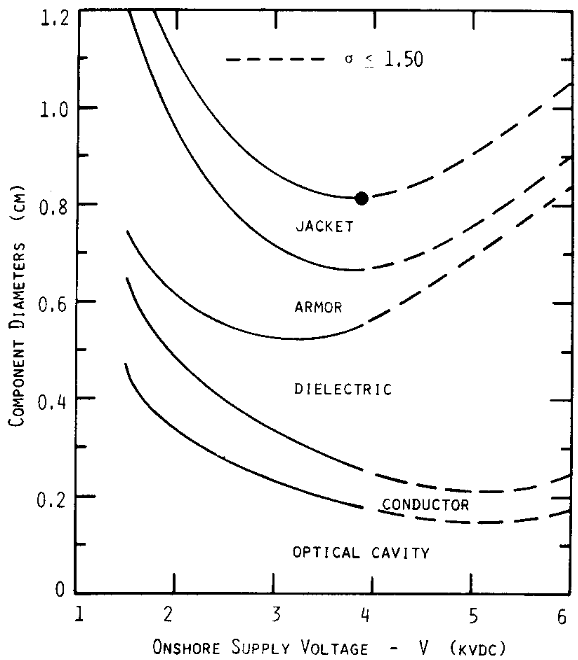

Figure (3)
Effects Of Varying V

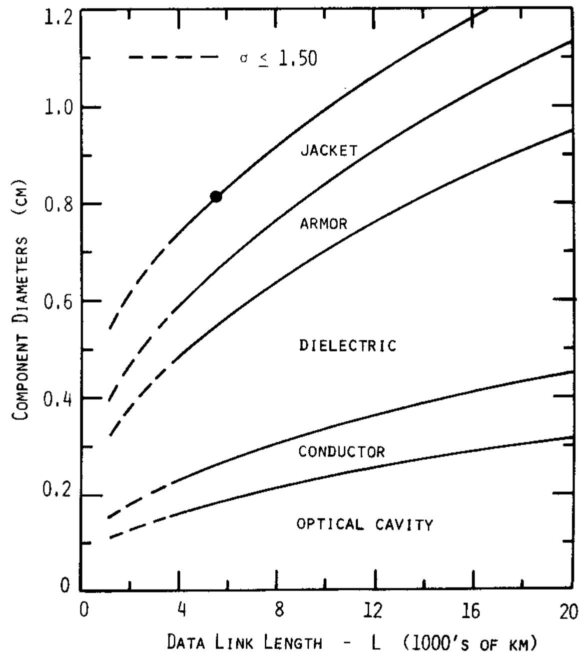

Figure (4)
Effects Of Varying L

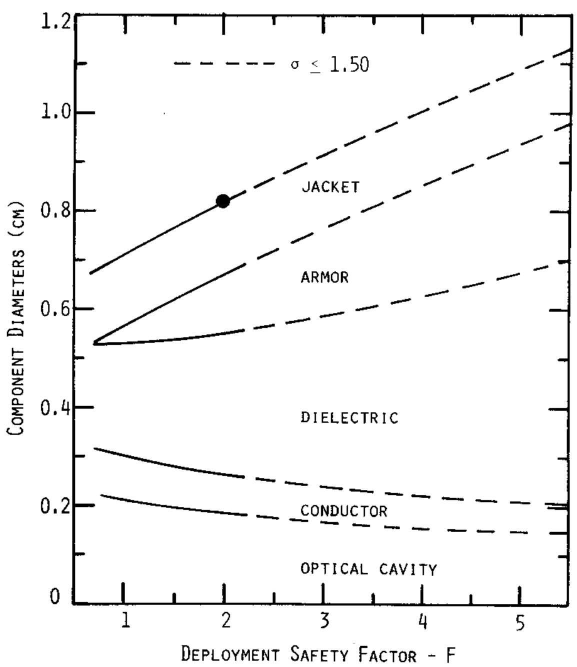

Figure (5)
Effects Of Varying F

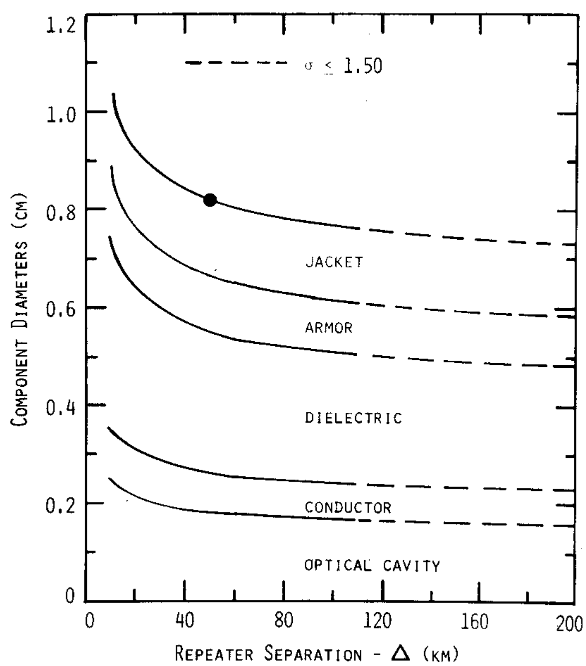

Figure (6)
Effects Of Varying A

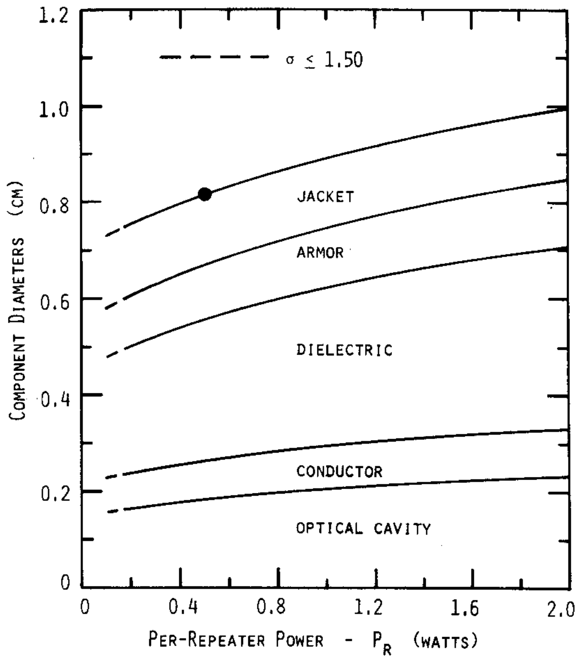

Figure (7)
Effects Of Varying P_R

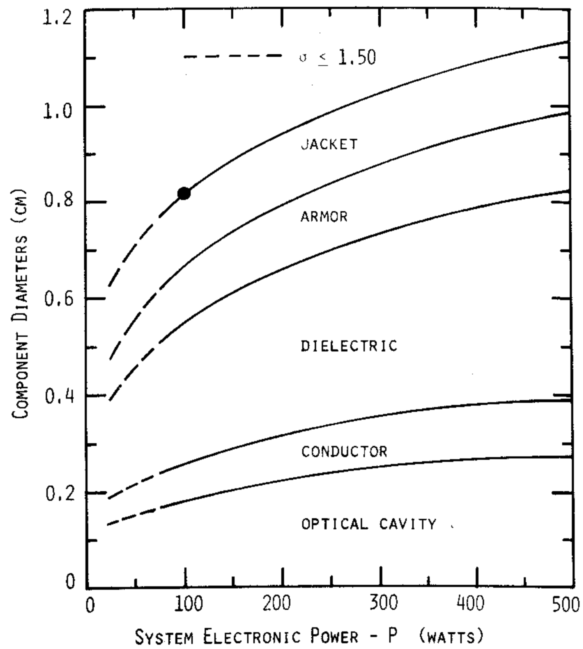

Figure (8)
Effects Of Varying P

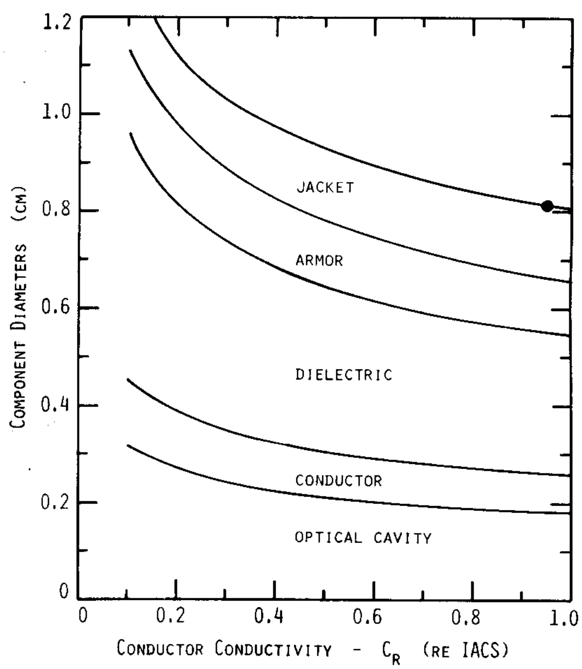

Figure (9)
Effects Of Varying C_R

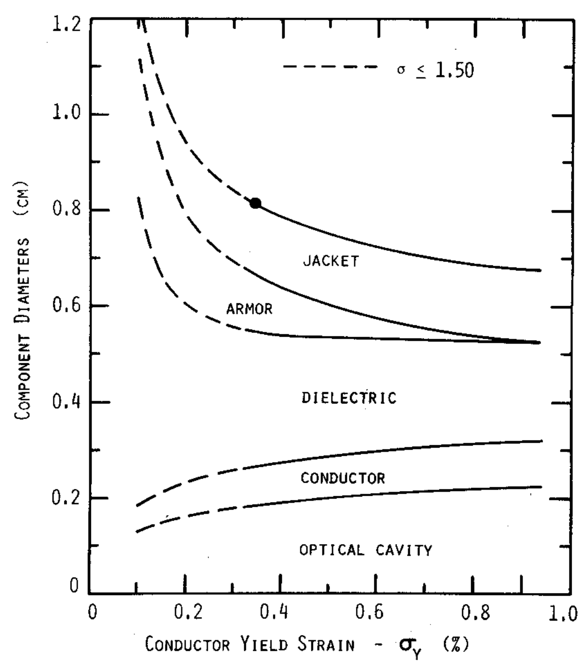

Figure (10)
Effects Of Varying σ_y

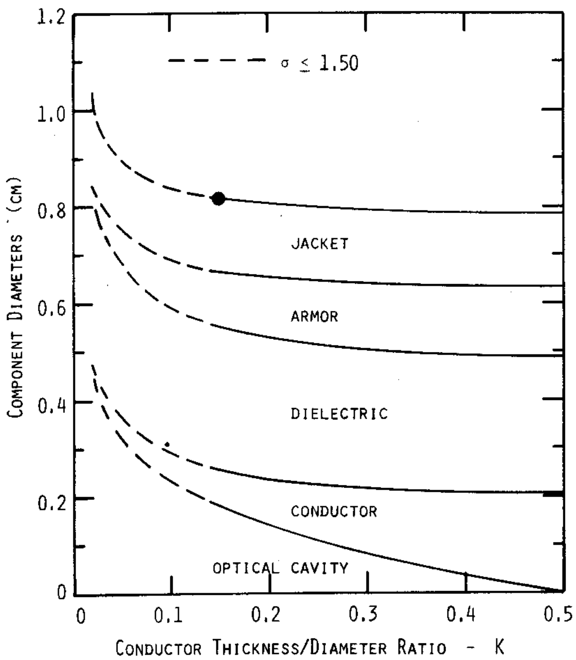

Figure (11)
Effects Of Varying K

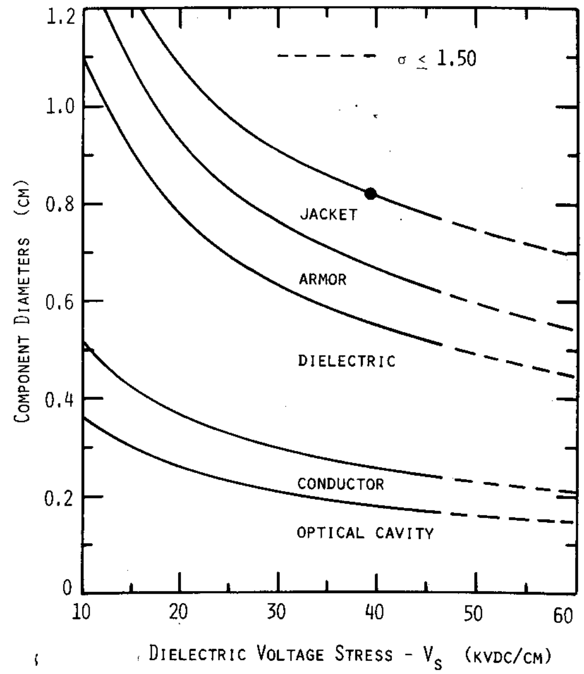

Figure (12)
Effects Of Varying V_s

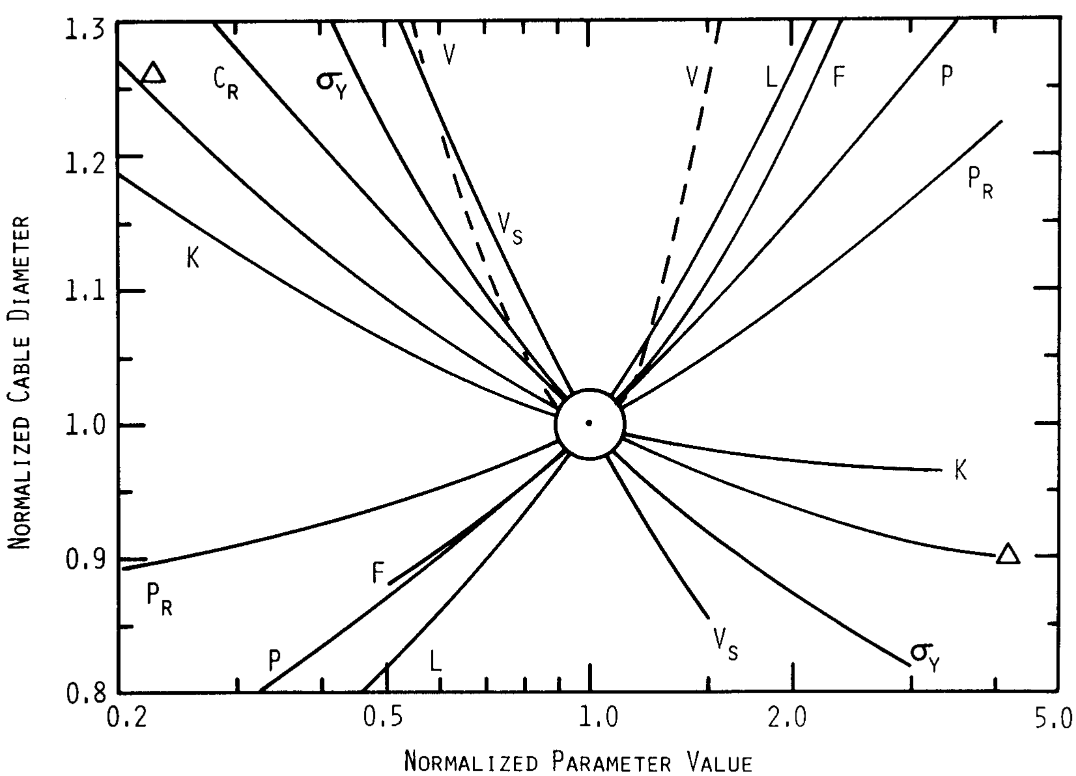

Figure (13)
Comparative Parameter Sensitivities

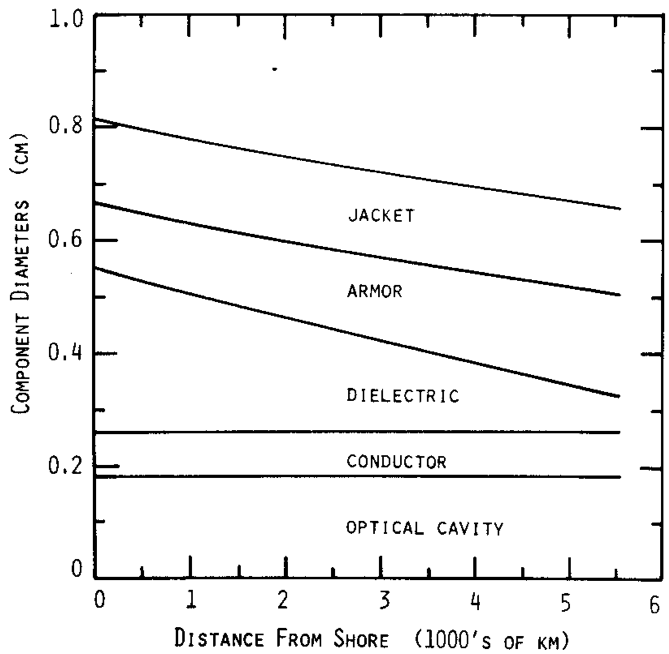

Figure (14)
Effects Of Diameter Tapering