Studies on Designing of Submarine Optical Fiber Cable

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Abstract—**This paper describes important studies necessary to design submarine optical fiber cables. These include a study for deciding the optimum single-mode fiber parameters to suppress losses during cabling, cable laying, and so on. It also includes a study on the necessary fiber proof test conditions to prevent fiber breakage during cable handling, that is, during cable laying and recovery and to assure long-term fiber reliability.**

Submarine optical fiber cable sea trial results are also stated for cables designed applying these studies.

I. Introduction

There is a possibility of realizing high-performance submarine optical fiber cables by applying the excellent characteristics of optical fibers to submarine cables. Certain cable structure proposals and various reports on experiments have already been made [1]-[4], and similar studies on submarine optical fiber cables are now under way in diverse fields of application.

The field of optical fibers has already developed so much that low-loss 0.5 dB/km and 0.2 dB/km single-mode fibers [5], [6] can be produced. The advantages of submarine optical fiber cables are increasing.

This paper deals with outcomes of studies on designing submarine optical fiber cables. The studies to be introduced here deal with optical fiber parameters that can reduce the loss variation caused by cabling and laying and with the strength of optical fibers required to endure cable laying and repair work and to prolong reliability. This paper also includes the results of an ocean test which was conducted taking into account the outcomes of these studies. The paper further indicates that the prospects are good for developing such submarine optical fiber cables.

II. Studies on Selection of Single-Mode Optical Fiber Parameters

We discuss here how to select the optical fiber parameters which contribute to limiting as much as possible the loss from cabling and/or laying.

There are several factors which cause transmission loss over a given relay link of a submarine optical fiber cable system, and these are examined.

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A. Coupling Loss Between Semiconductor Laser and Single-Mode Fiber

The output field pattern from a semiconductor laser and that of the LP_{01} mode of a fiber [7] can be approximated by Gaussian distribution. As shown in Fig. 1, the coupling efficiency can be estimated by the equation shown below, when the semiconductor laser facet and the fiber-end facet are set Z μm apart [8]:

$$\eta = \frac{4\omega_1\omega_2\omega_0^2}{[(\omega_1^2+\omega_0^2)^2+\lambda^2Z^2/\pi^2]^{1/2}[(\omega_2^2+\omega_0^2)^2+\lambda^2Z^2/\pi^2]^{1/2}} \quad (1)$$

where ω_1 and ω_2 indicate the spot sizes of the semiconductor laser vertical and lateral to its substrate plane, ω_0 is the spot size of the LP_{01} mode, and λ is the optical wavelength.

The spot size of the LP_{01} mode can be expressed approximately by the following equation [9]:

$$\omega_0/a = 0.65 + 1.619/V^{3/2} + 2.879/V^6 \quad (2)$$

where a is the core radius of the fiber and V is normalized frequency.

Fig. 2 shows the coupling loss α_{c0} between a semiconductor laser operating at 1.3 μm and a fiber, which was found by using the measured spot sizes of the semiconductor laser. The following values are used: ω_1 = 1.49 μm and ω_2 = 1.24 μm [10], and the distance between end faces Z = 10 μm. It indicates the loss as an equal loss curve on the plane of relative retractive index difference and core diameter; it is shown that there is an optimum relative refractive index difference and core diameter to minimize the coupling loss. This can be accounted for by the fact that a greater relative refractive index difference leads to a smaller beam waist of the LP_{01} mode, and the latter can be well matched with the field pattern of the semiconductor laser. Propagation can only be achieved in the LP_{01} mode while the normalized frequency V is less the 2.4. If frequency V exceeds 2.4 then propagation must be the multimode operation region. Fig. 2 shows only the single-mode operation region.

B. Bare Fiber Transmission Loss

The losses of bare fiber are generally caused by ultraviolet absorption, infrared absorption, Rayleigh scattering, and waveguide imperfections. The losses caused by ultraviolet absorp-

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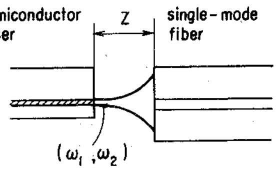

Fig. 1. Coupling between semiconductor laser and single-mode fiber.

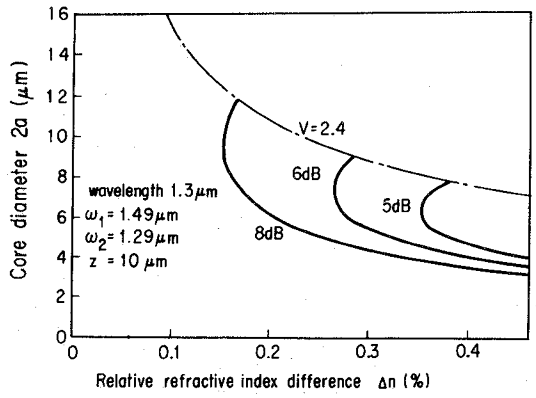

Fig. 2. Coupling loss between semiconductor laser and single-mode fiber.

tion α_{UV}, infrared absorption α_{IR}, and Rayleigh scattering α_R can be expressed by the following equations [11]:

$$\alpha_{UV} = \frac{15.42\Delta n}{4.46\Delta n + 60} 10^{-2} \exp\left(\frac{4.63}{\lambda}\right) \quad [\text{dB/km}] \tag{3}$$

$$\alpha_{IR} = 7.81 \times 10^{11} \exp\left(-\frac{48.48}{\lambda}\right) \quad [\text{dB/km}] \tag{4}$$

$$\alpha_R = (0.75 + 0.45\,\Delta n)/\lambda^4 \quad [\text{dB/km}] \tag{5}$$

where Δn (percent) denotes the relative refractive index difference between core and cladding. The waveguide imperfection loss α_I is mainly attributable to a micro variation of the core-cladding interface, as well as to residual bubbles; this type of loss can be assumed to be independent of the wavelength and constant. Hence the average of the measured values [15], as shown below, is considered an appropriate value:

$$\alpha_I = 0.2 \quad (\text{dB/km}).$$

C. Loss from Cabling and Laying

When a cable is made of optical fibers and is laid, the fiber loss is increased by the lateral pressure applied locally. Fig. 3 shows the mean values of measured losses before and after the cabling and laying in our field trial for nonrepeater submarine optical fiber cable [12]. The mean parameter values for the single-mode fiber include for the core diameter $2a = 10.0$ μm, and for the relative refractive index difference $\Delta n = 0.24$ percent. The measured loss before loading on the laying ship includes the loss caused by cabling and splicing. The loss increase caused by cabling and laying only is discussed. After cabling and laying increased losses were observed for wavelengths longer than 1.5 μm; these losses are estimated to be an accumulation of losses caused by numerous bends caused locally by lateral pressures on the fibers. It is hard, however, to individually measure the radius of curvature and length of each

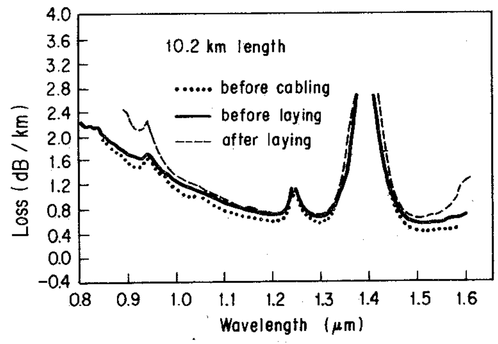

Fig. 3. Excess loss due to cabling and laying.

actual bend. Thus, we assumed that the even bends at a given radius occurred over the whole fiber. Bending loss α_b for the LP_{01} mode can be expressed by the following equation [13]:

$$\alpha_b = \frac{\sqrt{\pi}\, u^2 \exp\left[-\frac{2}{3}(w^3/\beta^2)R_c\right]}{2w^{3/2} V^2 \sqrt{R_c}\,[K_1(wa)]^2} \tag{6}$$

where β indicates the propagation constant in the LP_{01} mode, u and w are the normalized transverse propagation constants in the core and cladding, R_c is the radius of curvature of bending, and K_1 is a modified Bessel function of order 1. On the basis of the above assumption we can estimate the equivalent radius of curvature of bending caused by the cabling and laying to be $R_c = 40$ mm corresponding to the loss α_{cl} caused by cabling and laying, which are shown in Fig. 3.

D. Splicing Loss

The splicing loss may be attributed to 1) the core axial displacement, 2) the angular displacement, and 3) the end face imperfection.

We discuss here the main loss factor, viz. the core axial displacement. The loss α_s resulting from a given axial displacement χ can be calculated by the following equation [14]:

$$\alpha_s = 4.34 K_x (\chi/a)^2$$
$$K_x = \frac{1}{2}\left[\frac{J_0(u)}{J_1(u)} w\right]^2 \tag{7}$$

where J_0 and J_1 are Bessel functions of order 0 and 1. On the basis of the measured loss from splicing using a monitored fusion machine [15], we assume the mean axial displacement χ_{av} to be 1.25 μm. The total splicing loss should therefore be

$$(L_t/l_p + 3)\alpha_s \qquad (\chi = 1.25\ \mu\text{m})$$

where L_t indicates each relay link (km), l_p (km) is a single piece length of cable, and four splices are provided in each repeater.

E. Optimum Parameters

The total loss α of output light from the time of output from the semiconductor laser until it reaches the optical receiver can be estimated by summing up the different losses as mentioned in the preceding paragraph. Hence the following can be established:

$$\alpha = \alpha_{co} + \alpha_{UU} + \alpha_{IR} + \alpha_R + \alpha_I + \alpha_{cl} + (L_t/l_p + 3)\,\alpha_s. \tag{8}$$

Fig. 4 shows the total loss α as an equal loss curve on the plane

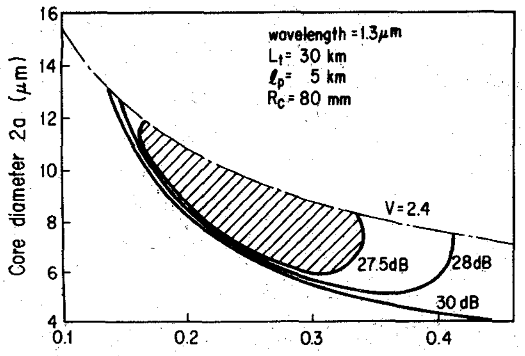

Fig. 4. One repeater spacing overall loss when R_c = 80 mm.

of relative refractive index difference and core diameter, when a given relay link is 30 km and each piece length is 5 km. There is a region where the minimum loss exists in this plot of the core diameter and relative refractive index difference; the area in which the total loss is less than 27.5 dB and which is a single-mode region is shown in Fig. 4 by the hatched area. In plotting this diagram we calculated R_c to be 80 mm, considering it possible to enlarge the equivalent radius of curvature from the cabling and laying effect by means of improved cabling techniques and cable structures.

The core diameter should be 7-10 μm and the relative refractive index difference 0.22-0.32 percent, while the total loss should be less than 27.5 dB. Fig. 5 shows the total loss where the relative refractive index difference is the abscissa; a minimum loss of 27 dB is possible when the core diameter is 9 μm and Δn = 0.23 percent. All the losses caused by the various factors are shown by the dotted lines in the diagram. The coupling loss, bare fiber loss, and splicing loss change gradually. However, the losses caused by cabling and laying rapidly increase when the value Δn becomes smaller.

Based on the data of Section II-C, the equivalent radius is 40 mm. In this case, the optimum fiber parameters are relative refractive index difference Δn = 0.28 percent and core diameter $2a$ = 9 μm.

III. Elongation of Cable and Optical Fiber During Laying and Recovery

Great tension is applied to the submarine optical fiber cable during laying and recovery. The optical fibers should be strong enough to absorb such elongation. In this section we discuss the elongation of cable and optical fiber during laying and recovery for the purpose of determining the required strength of optical fiber.

A. Tension During Laying

Assuming the underwater weight of the submarine optical fiber cable per unit length to be W and the laying depth to be h, the underwater cable weight is represented by Wh. To this is added dynamic tension caused by waves and the rolling of the laying ship. The total tension on the cable during laying can then be expressed by the following equation:

$$T = \alpha_1 Wh \tag{9}$$

where α_1 is the coefficient based on dynamic tension.

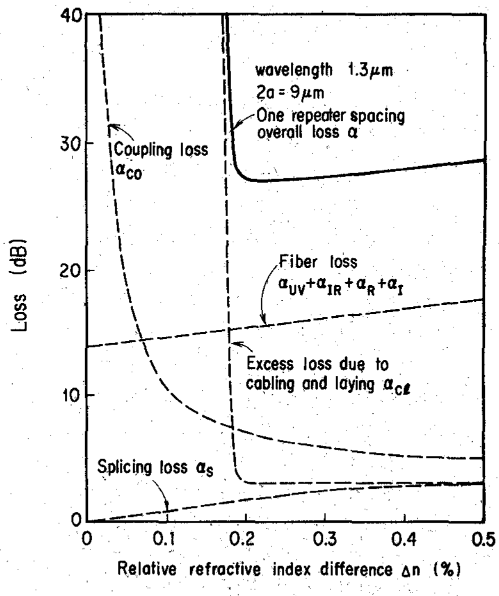

Fig. 5. Loss dependency on Δn.

We set α_1 = 1.5, taking into account the tension variation in the sheave onboard caused by waves and the variations in the cable feeding speed [16].

B. Tension During Recovery

There are two cable recovery methods. With one, the cable is raised in a catenary shape without cutting it (cable raising method). With the other, the cable is cut and taken up from the cutend (cable recovery method).

1) Cable Raising Method: Greater tension is generally applied to the cable during raising than during laying. This is caused by the friction between the sea bottom and the cable itself. If the cable is raised in the catenary shape, its tension during raising can be expressed by the following equation [17]:

$$T = \alpha_2 (\epsilon, \mu) Wh \tag{10}$$

where ϵ denotes the slack and μ denotes the friction coefficient on the sea bottom. A detailed description of α_2 is given in Appendix I. To set α_2 = 2.5 in a calculation based on the equation shown in Appendix I, it is sufficient to set the slack ϵ to 5 percent or more if the friction coefficient on the sea bottom μ = 0.3, or to 7 percent or more if μ = 0.5. For the following examination, we further set the design target of α_2 = 3.0, considering a variation in dynamic tension of 0.5 Wh due to the ship.

2) Cable Recovery Process: The following equation applies to the estimation of tension when the cable is cut and raised from its cut end [18]:

$$T = \alpha_3 (\theta_s, H, v) Wh \tag{11}$$

where θ_s denotes the recovery angle, H is the hydrodynamic coefficient, and v is the ship speed. A detailed description of α_3 is also given in Appendix II. Since the hydrodynamic coefficient of the cable structure under study was about 60 (degree · knot), if we set the ship speed v = 1 knot, and the recovery angle θ_s = 80° or more, almost perpendicular, it is sufficient to estimate that α_3 = 2.0, based on the equation shown in Appendix II. Considering the variation of dynamic tension to be 0.5 *Wh*, we set the design target to $\alpha_3 = 2.5$.

C. Elongation of Submarine Optical Fiber Cable During Laying and Recovery

Applying the theory in Section III, we estimated the cable tension during laying and recovery using 1.5 *Wh* for the laying, 3 *Wh* for the raising, and 2.5 *Wh* for the recovery process. Fig. 6 shows the structure of the submarine optical fiber cable of understudy and Fig. 7 shows the elongation characteristics of the cable. The underwater weight of the cable is about 0.64 kg/m.

Tables I and II show the tension during laying and recovery, as well as the elongation of the optical fiber during laying and recovery, all of which were estimated based on the aforementioned theory and the cable elongation characteristics shown in Fig. 7. The elongations of both the cable and optical fiber were assumed equal because we designed the cable and the fibers were to be drawn out equally. However, the elongation value for the optical fiber of 0.08 percent was added as bending distortion ϵ_b in our study.

In the cable raising from a depth of 6000 m the cable tension was 11.6 tons, as shown in Table I, meaning that the possibilities of breaking such a cable would be quite high, if the designed cable tension were 12 tons.

The estimated tension when lifting the cable from a depth of 6000 m is not therefore shown in Table II.

IV. Assurance of Optical Fiber Strength

Great tension is applied to the cable during laying and recovery, as already mentioned, and the fibers are thus drawn out. To assure that the optical fibers will not break for a long time, it is essential to set up certain means of assuring the optical fiber strength. One effective means of doing so is to develop optical fibers which hold up during proof tests.

As is well known, the lifetime of optical fibers depends on microscopic cracks. According to Charles' model [19] the growing speed of cracks can be expressed by the following equation when a certain strain is applied to the optical fiber:

$$\frac{dx}{dt} = C\sigma^n \left(\frac{x}{\rho}\right)^{n/2} e^{-A/RT} \tag{12}$$

where x is the size of the crack, n and R are the constants that are determined by the atmosphere, ρ is the curvature of the crack tip, T is the absolute temperature, and C and A are constants.

If the growing crack size is x_1 when static load σ is applied to a fiber having initial cracks of size x_0 for period t, the following equation can be established by integrating (12) with respect to time:

$$\frac{1}{1-n/2}\left(x_1^{1-n/2} - x_0^{1-n/2}\right) = C\left(\frac{1}{\rho}\right)^{n/2} e^{-A/RT} \cdot \sigma^n \cdot t. \tag{13}$$

The above equation means that the degrees of crack growth can be well expressed by $\sigma^n \cdot t$ if the atmosphere is under the same condition. The values of n have already been experimentally obtained [20], $n = 20$–25 in a dry atmosphere and $n = 15$–20 in wet atmosphere.

Assuming the distortion to be applied to the optical fibers under the proof test to be σ_p, the time of test t_p, and the sum of distortions to be applied to the optical fiber and time of application for the cable manufacturing, laying, recovery, and repair to be $\sum_{m=1}^{m=M} \sigma_{rm}^n t_{rm}$, the following equation can be established (see Appendix III):

$$\sum_{m=1}^{m=M} \sigma_{rm}^n t_{rm} = \left[\left(1 + \frac{\ln(1-F_r)}{\ln(1-F_p)}\right)^{1/b} - 1\right] \sigma_p^n t_p. \tag{14}$$

The term $(1 - F_p)$ in the above equation indicates the survival probability of an optical fiber of length L, when it is subjected to the proof test with the distortion σ_p and the time t_p. It can be estimated by an equation in Appendix IV. The distortion σ_p can be given generally by the elongation strain under the static load test; $(1 - F_r)$ is the survival probability of optical fibers over a full length cable when the distortion

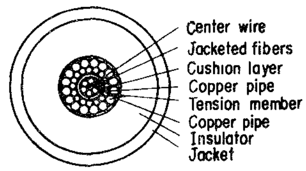

Fig. 6. Cable structure.

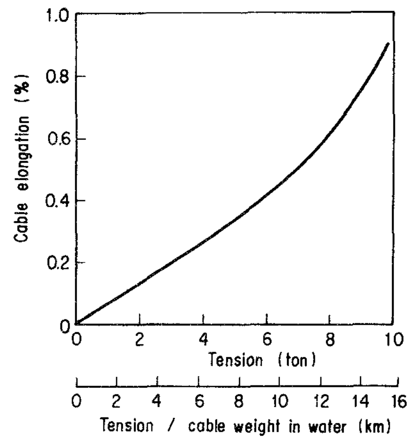

Fig. 7. Cable elongation characteristics.

TABLE I
Cable Laying, Raising, and Recovery Tension

Water depth	Cable laying	Cable raising	Cable recovery
4000 m	3 8 tons	7 6 tons	6 4 tons
5000 m	4 8 tons	9 6 tons	8 0 tons
6000 m	5 8 tons	(*1) 11 6 tons	9.6 tons

(*1) Breaking possibility is very great

TABLE II
Fiber Elongation

Water depth	Cable (*2) laying	Cable (*3) raising	Cable (*2) recovery
4000m	0 34 %	0 58 %	0.54 %
5000m	0 41 %	0 86 %	0 72 %
6000m	0 49 %	—	0 93 %

(*2) Bending strain of 0.08% is added.
(*3) Bending strain is not added

$\sum_{m=1}^{m=M} \sigma_{rm}^n t_{rm}$ is applied after being successfully tested using the proof test (see Appendix III). Terms $1 - F_p$ and $1 - F_r$ can be expressed as follows:

$$1 - F_p = \exp\left[-L\left(\frac{\sigma_p^n t_p}{\sigma_0^n t_0}\right)^b\right] \tag{15}$$

$$1 - F_r = \exp\left[\ln(1 - F_p)\left\{\left(1 + \frac{\sum_{m=1}^{m=M} \sigma_{rm}^n t_{rm}}{\sigma_p^n t_p}\right)^b - 1\right\}\right]. \tag{16}$$

Table III shows examples of the mean survival fiber length of optical fibers I and II, which were measured with the proof load σ_p and t_p.

Research on making fibers stronger is now being conducted. The data shown in Table III are two examples under study. As two different proof loads σ_p were applied to the same fiber, the unknown coefficients of b and $\sigma_0^n t_0$ can be determined by (15) as mentioned in Appendix IV. The experimental equations thus attained are as shown below:

$$\text{Fiber I} \quad \cdots F_p = 1 - \exp\left[-L \cdot \left(\frac{\sigma_p^n t_p}{4.41 \times 10^{25}}\right)^{0.188}\right] \tag{17}$$

$$\text{Fiber II} \quad \cdots F_p = 1 - \exp\left[-L \cdot \left(\frac{\sigma_p^n t_p}{7.84 \times 10^{39}}\right)^{0.103}\right]. \tag{18}$$

Table IV shows the distortion to be applied to the optical fibers during cable laying and recovery and its duration, both of which were determined from Table II. With the procedure shown in Table IV, it is possible to find the $\sum_{m=1}^{M} \sigma_{rm}^n t_{rm}$ that will be applied to the optical fibers throughout the cabling and repair. Accordingly, (14)-(18) can be applied to find the required proof test conditions for the survival probability $(1 - F_r)$ of optical fibers over the full cable length. Table V and Fig. 8 show typical calculations of the required proof test conditions corresponding to each cable laying depth. The difference of the proof test values is small between fiber I and fiber II.

V. Sea Trial

Our examinations mentioned above resulted in determination of optical fiber parameters that may minimize losses during cabling and laying, and also in the estimation from the elongation characteristics of trial cables of optical fiber elongation during laying, raising, and recovery. A technique has also been defined for setting up proof conditions to assure prolonged reliability of optical fibers and the endurance of optical fiber elongation.

A sea trial was then conducted on the transmission line that was structured shown in Fig. 9 based on the aforementioned design techniques. The cable structure is shown in Fig. 6, and the parameters and various characteristics of the fibers used in the test are shown in Table VI.

In Fig. 9, J.B. 1 and J.B. 2 mean joint boxes 1 and 2, respectively. C.E. stands for cable end.

In this cable, four single-mode fibers are included. Two fibers are spliced at the cable end.

TABLE III
MEAN SURVIVAL FIBER LENGTH EXAMPLES AFTER PROOF TEST

proof test strain	fiber(I)(*1)	fiber (II)(*2)
1.00 %	——	8 km
1.13 %	29 km	——
1.50 %	10 km	3.5 km

(*1) proof test time t = 1 sec, coated fiber
(*2) proof test time t = 2 sec, non-coated fiber

TABLE IV
σ_r AND t_r CORRESPONDING TO EACH CABLE HANDLING PROCESS (n = 20)

Water depth	Handling process	σ_r (%)	t_r (sec)	$\sigma_r^n t_r$	$\sum_{m=1}^{M} \sigma_{rm}^n t_{rm}$ (*1)
4000m	initial laying	0.34	8700	3.71×10^{-6}	2.16×10^{-1}
	raising	0.58	8400	1.56×10^{-1}	
	recovery	0.54	13200	5.87×10^{-2}	
	joining	0.42	57600	1.68×10^{-3}	
	laying	0.34	8700	3.71×10^{-6}	
5000m	initial laying	0.41	10800	1.95×10^{-4}	5.37×10^{2}
	raising	0.86	10500	5.14×10^{2}	
	recovery	0.72	16500	2.31×10^{1}	
	joining	0.52	57600	1.20×10^{-1}	
	laying	0.41	10800	1.95×10^{-4}	
6000m	initial laying	0.49	13200	8.40×10^{-3}	4.22×10^{3}
	raising(*2)	——	——	——	
	recovery	0.93	18000	4.22×10^{3}	
	joining	0.64	57600	7.66×10^{0}	
	laying	0.49	13200	8.40×10^{-3}	

(*1) A 20-year Residual strain of 0.2 % has been added.
(*2) In this case cable length affected by cable raising is not used.

TABLE V
NECESSARY PROOF TEST STRAIN CORRESPONDING TO WATER DEPTH

water depth	fiber (I)	fiber (II)
4000 m	1.38 %	1.42 %
5000 m	2.22 %	2.18 %
6000 m	2.52 %	2.45 %

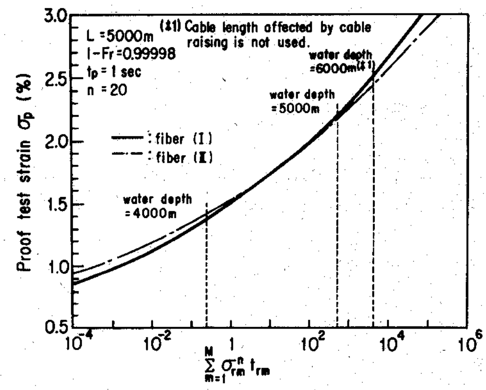

Fig. 8. Relation between σ_p and $\sum_{m=1}^{M} \sigma_{rm}^n t_{rm}$.

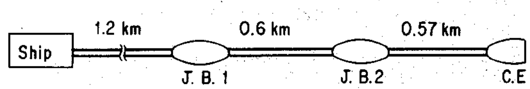

Fig. 9. Line construction.

TABLE VI
FIBER PARAMETERS AND CHARACTERISTICS

Fiber parameters		2a = 9~12 μm Δn = 0.25~0.30 % λc = 1.1~1.2 μm ᾱ = 0.56 dB/km (λ=1.3 μm)
Excess loss	Cabling	mean--- 0.06 dB/km max --- 0.16 dB/km
	Splices	J.B. 1--- 0.01 dB J.B. 2--- 0.32 dB mean --- 0.16 dB

Two measurements are conducted. One is for fiber loss. The other is for fiber elongation.

In the recovery of cable laid 500 m deep, no increases in cable loss were observed, as shown in Fig. 10.

Fig. 11 shows optical fiber elongation in sea trial laying experiments conducted at a water depth of 1000 m.

The solid line shows measured fiber elongation during cable laying. Fibers were spliced at the cable end (C.E. in Fig. 9). The elongation was measured in the ship from pulse delay changes using a pulse laser diode.

The dotted line shows the calculated value of cable elongation based on the cable elongation characteristics shown in Fig. 7 and cable laying tension.

The calculated and measured values show good agreement. This means that the cable and fiber elongation are the same.

VI. Conclusion

The aforementioned studies have pointed out the bright prospects for the fundamental technique of using optical fibers in submarine cables. The following problems still require solutions, which must be found prior to commercialization of the optical fibers.

1) Development of stronger longer fibers.
2) Establishment of a manufacturing technique for long cables, extending over tens of kilometers.
3) Setup of repair techniques.
4) Establishment of fault location technique for long cables.

Appendix I
$\alpha_2(\epsilon, \mu)$ [17]

The tension under recovery can be found by the following equation:

$$T = \frac{Wh}{1 - \cos\theta} = \alpha_1 Wh \tag{A1}$$

where θ indicates the angle of cable recovery, which can be found by the following equation:

$$\theta = \cos^{-1} \frac{1}{\sqrt{1 + \left(\frac{l_0}{\mu l}\right)^2}}. \tag{A2}$$

The term $l_0/\mu l$ can be expressed as follows:

$$\frac{l_0}{\mu l} = \sinh \frac{\frac{l_0}{\mu l} - \frac{\epsilon}{\mu}}{1 + \epsilon} \tag{A3}$$

where l_0 indicates the full length of the catenary cable, μ is the friction coefficient of the cable on the sea bottom, l is the cable length subject to friction, and ϵ is the cable slack during laying. The value α_2 can be given by (A1), (A2), and (A3).

Appendix II
$\alpha_3(\theta_s, H, v)$

The value α_3 can be found by the following equation [18]:

$$\frac{\alpha_3 - 1}{\alpha_3} = \left[\tan^2\theta \, \frac{\cos\theta + \cos\theta_s}{1 - \cos\theta\cos\theta_s}\right]^{1/\gamma} \tag{A4}$$

where

$$\gamma = (2 - \sin^2\theta)/\sin\theta \tag{A5}$$

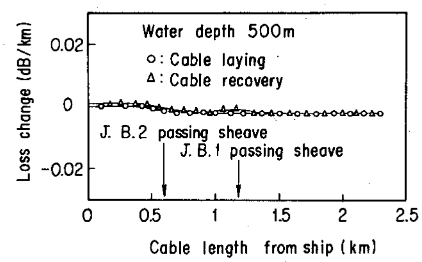

Fig. 10. Loss change caused by cable laying and recovery.

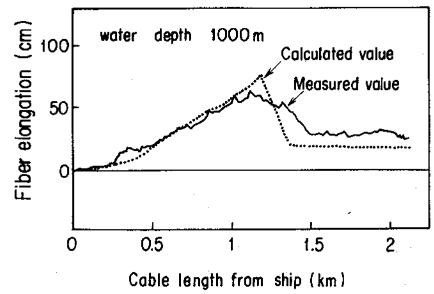

Fig. 11. Fiber elongation caused by cable laying.

$$\cos\theta = \sqrt{1 + \frac{1}{4}\left(\frac{H}{v}\right)^2} - \frac{1}{2}\left(\frac{H}{v}\right)^2 \tag{A6}$$

where θ_s = recovery angle, H = hydrodynamic coefficient (degree · knot), and v = ship speed.

Appendix III
Setup of (14)

The value $\sigma^n t$ is the basic amount that breaks the optical fiber. If, therefore, $y = \sigma^n t$ for an optical fiber of a given length L, its cumulative breaking probability can be given as $F(y, L)$, and the cumulative distribution of the number of cracks over a unit length of cable can be expressed by $N(y)$. Then the following equation can be set up for the cumulative breaking probability when y increases by dy:

$$F(y + dy, L) - F(y, L) = \left(L \frac{dN}{dy} \cdot dy\right) \{1 - F(y, L)\}. \tag{A7}$$

By integrating and reshaping the above equation, the following equation can be attained:

$$F(y, L) = 1 - \exp\left[-LN(y)\right]. \tag{A8}$$

If $N(y)$ is found, $F(y, L)$ can be also found.

Olshansky proves $N(y)$ can be expressed by $(\sigma^n t/\sigma_0^n t_0)^b$ [21], where σ_0, t_0, and b are constants. Hence, (A8) can be converted as follows:

$$F(\sigma^n t, L) = 1 - \exp\left[-L\left(\frac{\sigma^n t}{\sigma_0^n t_0}\right)^b\right]. \tag{A9}$$

The value b in the above equation is the slope in the Weibull distribution probability plot of the time required for failure when measured by applying a given load. In this report we find $\sigma_0^n t_0$ and b using a method to be described later (see Appendix IV). We assume the cumulative breaking probability of an optical fiber before the proof test to be

$$F_s = F(\sigma_s^n t_s, L) \tag{A10}$$

and the same during the proof test to be

$$F_p = F(\sigma_p^n t_p, L) \tag{A11}$$

and the probability after the proof test to be

$$F_r = F(\sigma_r^n t_r + \sigma_p^n t_p, L). \tag{A12}$$

Hence the cumulative breaking probability F_r of the optical fibers undergoing the proof test can be found by the following equation:

$$F_r(\sigma_r^n t_r, L) = \frac{F_s - F_p}{1 - F_p}. \tag{A13}$$

Although the proof tests were conducted based on dynamic fatigue tests [22], our discussion in this report is made on the basis of a generally accepted proof test method that applies a static load.

To find F_r using (A9), the following equation can be established:

$$F_r(\sigma_r^n t_r, L) = 1 - \exp\left[-\frac{L}{(\sigma_0^n t_0)^b} \cdot \{(\sigma_r^n t_r + \sigma_p^n t_p)^b - (\sigma_p^n t_p)^b\}\right]. \tag{A14}$$

Equation (A11) can be expressed as follows, using (A9):

$$F_p = 1 - \exp\left[-\frac{L}{(\sigma_0^n t_0)^b}(\sigma_p^n t_p)^b\right]. \tag{A15}$$

Changing the form of the above equation, we get

$$\frac{\ln(1 - F_p)}{(\sigma_p^n t_p)^b} = -\frac{L}{(\sigma_0^n t_0)^b}. \tag{A16}$$

By substituting (A16) for (A14), the following equation is obtained:

$$F_r = 1 - \exp\left[\ln(1 - F_p)\left\{\left(1 + \frac{\sigma_r^n t_r}{\sigma_p^n t_p}\right)^b - 1\right\}\right]. \tag{A17}$$

Then by changing the form of (A17), the following equation can be set up:

$$\sigma_r^n t_r = \left[\left(1 + \frac{\ln(1 - F_r)}{\ln(1 - F_p)}\right)^{1/b} - 1\right]\sigma_p^n t_p. \tag{A18}$$

The value $\sigma_r^n t_r$ is the amount that specifies the deterioration of optical fiber strength, as already mentioned; the sum of distortion and its duration applied to the optical fiber after the proof test $\Sigma_{m=1}^{m=M} \sigma_{rm}^n t_{rm}$ must be less than $\sigma_r^n t_r$. Hence, the following equation can be established:

$$\sum_{m=1}^{m=M} \sigma_{rm}^n t_{rm} = \left[\left(1 + \frac{\ln(1 - F_r)}{\ln(1 - F_p)}\right)^{1/b} - 1\right]\sigma_p^n t_p. \tag{A19}$$

Appendix IV. How To Find b and $\sigma_0^n t_0$

Two constants, $\sigma_0^n t_0$ and b, of (A9) can be found in the following manner. Using a long-length optical fiber, we conduct a proof test to find the mean survival length L_{p1} of an optical fiber that gives 50 percent of F_p. Similarly, we find the mean survival length L_{p2} that gives 50 percent of F_p under different proof tests. Then two different equations of $\sigma_0^n t_0$ and b can be derived from (A15) so that the two parameters can be found for (A15).

Appendix V Relation Between Optical Fiber Length L and $(1 - F_r)$

Optical fiber length L is related to its survival probability $(1 - F_r)$. Equation (A9) makes it easy to understand the following relation existing between survival probability $(1 - F_{rp})$ of an optical fiber of length L_p and probability $(1 - F_r)$ of an optical fiber of the length L:

$$(1 - F_r) = (1 - F_{rp})^{L/L_p}. \tag{A20}$$

The above equation gives the survival probability of optical fibers over the full length L from $(1 - F_{rp})$.

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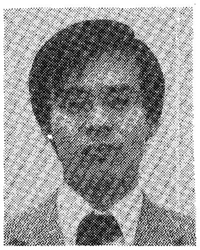

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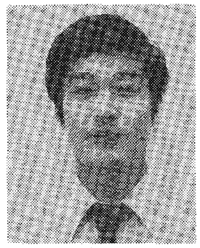

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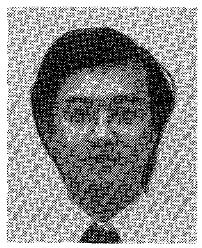

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