

DESIGN AND DEVELOPMENT OF STEAM RESISTANT FIBER OPTIC CABLE

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ABSTRACT

A systematic design and development of a novel Steam Resistant Loose Tube (LT) optical fiber cable is discussed. This design utilizes a hydrolytically and high temperature stable LT material. Moisture ingress into the cable core is highly suppressed by enclosing the optical core with a welded aluminum tube. Cable lifetime is increased substantially by using this design compared to standard polyethylene sheathed PBT LT cable designs. A mathematical model for the rate of change of MFI of PBT has been developed and used to justify this chosen cable design which meets all the mechanical and environmental requirements of Bellcore Technical document TR-TSY-000020, Issue 4, March 1990.

1.0 INTRODUCTION

Loose tube (LT) optical fiber cable designs have been widely used in industry to date. Polybutylene terephthalate (PBT) is commonly used as a preferred tube material because of its good mechanical and chemical characteristics, along with easy processibility.

Recently the deficiency of such an LT cable design was highlighted through the installation of such cables next to steam ducts in New York City and Cleveland. The underground steam ducts in these cities are approximately 80 - 100 years old and consequently are prone to steam leakage through aging and fatigue of steam pipes. In two specific instances, failure of steam pipes has been monitored recently. The average temperature and pressure of escaping steam is up to 400°F and 400 psi depending on the pipe size. (1) In both cases, the incipient failure resulted in the long term exposure of LT optical cable to such a harsh hot and humid

steam environment. The cumulative effect of such an exposure resulted in cable failures in both cases. A detailed examination of the failed cable sample revealed:

- (a) Catastrophic failure of PBT tubes (Fig. 1)
- (b) Swelling and degradation of fiber acrylate on-line coating (Fig. 2)



FIG.1. PHOTOGRAPH SHOWING DEGRADATION OF PBT TUBES IN A PLAIN SHEATH CABLE FIELD FAILURE.

The above scenario clearly highlighted the need for a more robust cable design which can be successfully used in such a hostile environment. In order to provide the high degree of reliability required for steam applications, cables must be designed using temperature and hydrolytically stable materials. Additionally, the UV acrylate coated fibers should be fully isolated from the ingress of moisture.

The aim of this investigation is to identify the engineering requirements

for steam environment applications. The study then identifies both tube and cable jacketing materials which are stable in such hostile environments. This paper discusses in detail the material compatibility studies undertaken along with the evolution of a new cable design based on a simple model and the results of experimental investigations.



FIG.2. PHOTOGRAPH SHOWING SWELLING AND DEGRADATION OF ACRYLATE ONLINE FIBER COATINGS.

2.0 THE STEAM ENVIRONMENT

The steam delivery systems in place in New York, Cleveland, Boston and elsewhere contain super-heated moisture at pressures to 150 psi or more, at temperatures to 400°F. Two modes of steam attack on fiber optic cables include the escape of steam through fractures in the antiquated piping system, or water external to the steam delivery system boiling on contact with the piping. For example, based on the thermodynamics of escaping steam from a 200 psi tunnel, at 400°F, it is estimated that the maximum exposure temperature to a neighboring cable is 250°F to 280°F. While this is an anticipated maximum exposure, practical experience indicates that the subject environment at the cable surface is below 212°F.

In order to get a comprehensive picture of the degradation of cable components in steam environments, the effects due to any chemicals used in these steam systems have to be quantified. Both in Cleveland and New York, the chemical constituents of steam are analyzed periodically. Table 1 shows such an analysis carried out for #2 and #4 steam canals of Cleveland. The chemical

constituents of steam are shown to be non-corrosive in nature. Similar data has also been obtained for steam canals in New York. Thus the degradation effects due to chemical constituents of steam are negligible and hence the primary degradation effects of concern in steam are mainly due to exposure to high temperature and humidity.

Table 1. Analysis of Chemical Constituents in City Water and Steam of Cleveland's #2 and #4 Main Steam Canals

Chemical Constituents (ppm)	City Water	Steam #2 Main Steam Canal	Steam #4 Main Steam Canal	Demineralized Water
Calcium	75	Nil	Nil	Nil
Magnesium	45	Nil	Nil	Nil
Sodium	20	10	5	5
Total Electrolyte	140	10	5	5
Bicarbonate	100	20	15	50
Carbonate	0	0	0	0
Hydroxyl	0	0	0	0
Sulfate	10	10	5	10
Fluoride	20	0	0	0
Chloride	30	20	20	30
Nitrate	0	0	0	0
Carbon Dioxide	0	0	0	0
pH	8.2	8.0	8.0	8.2
Conductivity	29.0	0.47	0.49	0.28
Silica	3	10	0	0
Iron	0	0	0	0
Turbidity	0	0	0	0
TDS	100	65	60	60
Color	0	0	0	0

Test data supplied by Cleveland Thermal Energy (courtesy of R. Henry Water Treatment Corp., Ohio)

3.0 MATERIAL REQUIREMENTS

The key issue is the survival of the delicate optical fibers when exposed long term to this high temperature steam. Since a high temperature steam environment is conducive to hydrolysis of both polyesters and acrylates, it is evident that standard PBT tubes in traditional loose tube cable constructions are inappropriate for the protection of optical fibers in this application. Alternative tube and/or jacket materials are therefore required. Ideal materials must fulfill four key requirements:

- 1) Materials must be stable to long-term exposure of at least 120°C.
- 2) Materials must be hydrolytically stable.
- 3) Materials must suppress moisture penetration to the vicinity of the optical fibers.
- 4) Materials should be readily processible using existing equipment.

Other key material attributes are good chemical and compressive resistance, high strength and low shrinkage.

3.1 Tube and Material Selection

High performance polymers like fluoropolymers offer one obvious choice for tube and jacket materials. In all four tube materials were evaluated here, namely:

Material A: A PVDF-based material with a stable temperature rating of around 250°F (PVDF).

Material B: An amorphous Polyethersulphone with a stable operating temperature of greater than 300°F (PES).

Material C: This is a copolymer of Ethylene & chlorotrifluoroethylene with stable operation around 270°F (E-CTFE).

Material D: Improved hydrolytic stability PBT.

Some properties of these selected tube materials are shown in Table 2.

3.2 Tube Processing

PVDF, PES and PBT are readily manufactured using standard LT Extrusion equipment. E-CTFE requires the use of a special Hest alloy Barrel and tooling. Excess fiber lengths are maintained in the desired range for PES, E-CTFE and PPT. However, PVDF material had lower melt strength and high post-extrusion shrinkage resulting in rather high and poorly controllable excess lengths. PVDF is therefore not acceptable candidate tube material at this time.

4.0 TUBE MATERIAL RELIABILITY TESTING

A comprehensive program was conducted to evaluate the performance of these candidate tube materials. Test details are outlined below.

4.1 Low Temperature Bend Test

Low temperature bend is performed by wrapping each tube ten times around a mandrel the same size as tube O.D. at -20°C and observing for any kinks or cracks in the tubes. Minimum soak time for each tube was two hours.

4.2 85°C/Jelly Aging Bend Test

After test I is completed, tubes (secured around mandrel ten times) are placed in a pan of Naptel 851 jelly. The pan is then placed in a temperature cabinet at 85°C for 30 days. Tubes are

checked for further signs of cracks after 5, 15 and 30 days aging respectively.

4.3 High Temperature Stress Cracking Test

Ten turns of samples of each material are wound on x 5.0 and x 10 mm mandrels respectively and aged for 30 days at 150°C/ambient air and 170°C/ambient air respectively. Samples were checked for cracks after 1, 7, 15 and 30 days aging respectively.

4.4 Tube Compression Test

Tube samples of each of these materials are placed between compression plates in an Instron Tensilometer and compressed at steady rate until 2700N load was reached. Effective tube modulus and yield load are calculated from the slope of the compression curve.

4.5 85°C/94% R.H. Tensile Aging Test

Dumbbell samples of materials are aged at 85°C/94% R.H. at different time intervals of 15, 31, 45 and 60 days, and tensile tested to evaluate degradation in material yield strength and elongation at yield.

4.6 PBT MFI Aging Test in 100°C Water

Two meter cable samples containing PBT tubes are boiled in 100°C water with cable ends isolated from water. Melt flow index of standard PBT and hydrolytically stable PBT tubes is measured and compared after different aging time intervals.

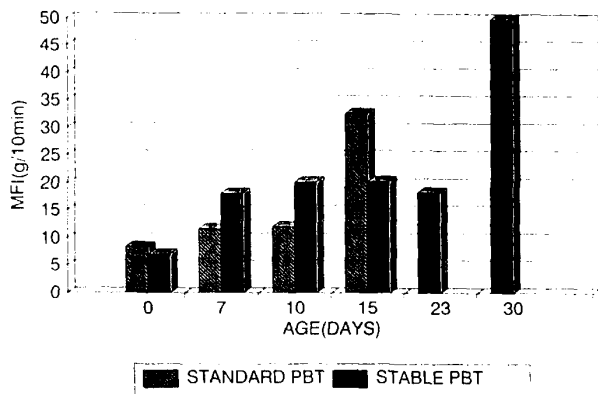
4.7 Tube Shrinkage Test

2 m tube samples are soaked for 24 hours at 120°C and tube shrinkage measured.

Results of tests 4.1 to 4.4 are tabulated in table 3. Both polyethersulphone and E-CTFE are shown to be superior in performance than the hydrolytically stable form of PBT in cyclic cold bend flex tests. Furthermore, no stress cracking is observed up to 30 days exposure at 170°C in ambient humidity applications.

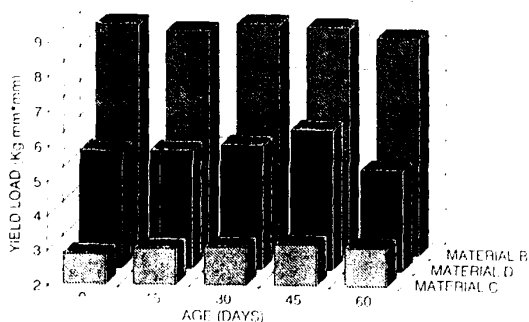
Fig. 3 shows the variation in MFI of the two types of PBT in 100°C boiling water conditions. It is clear that hydrolytically stable PBT shows an improvement but is still prone to hydrolysis at longer time interval and therefore it would be unsuitable for steam duct applications and is not considered further.

FIG.3 MFI VARIATION OF PBT'S
100 DEG. C BOILING WATER



Tensile aging data is shown in figure 4. PES has approximately four times higher yield load as compared to E-CTFE even after aging for 60 days at 94% R.H. Tube shrinkage data in table 3 also shows that PES has the lower amount of shrinkage compared to E-CTFE. Low modulus and low shrinkage are beneficial in minimizing contraction which may cause attenuation increases at low temperature; both E-CTFE and PES are expected to perform well in cables.

FIG.4 YIELD LOAD VERSUS AGING TIME
85 DEG.C & 94% R.H.



Based on the excellent mechanical properties then, the best choice of tube material is either PES or E-CTFE for steam environments.

5.0 CABLE DESIGN

In completing the design of a cable for steam duct application, the following criteria were established:

1. Ingress of moisture into the cable core and to the fibers must be either suppressed totally or otherwise retarded sufficiently for the fibers in the cable to operate for years without any adverse effects.
2. As stated earlier, the tube material selected must be hydrolytically and temperature stable up to 120°C.
3. The cable jacket should also be selected such that it is hydrolytically and temperature stable up to 120°C, although by a judicious design of intermediate moisture barriers surrounding the cable core, ordinary high density or medium density polyethylene (PE) is sufficient.
4. The cable should meet all other mechanical and environmental requirements normally expected of LT Fiber Optic Cables, i.e., as specified in Bellcore document TR-TS-20, Issue 4, (2).

5.1 Cable Design Iteration

In order to arrive at an optimized design based on the principles of multi-layer moisture barriers incorporated within the cable structure, a systematic experimental investigation was conducted. The starting point was a standard non-armored polyethylene sheathed PBT LT cable design. The performance of plain sheathed cable was compared to cables containing successively improved intermediate metallic barriers, utilizing LAP tapes, and welded aluminum tubing.

Cable performance was evaluated based on cable lifetime. Because of the known instability of PBT, Melt Flow Index (MFI) of cabled PBT tubes was used as the primary indicator of moisture ingress to the core. Additionally, Oxidation Induction Time (OIT) of the PE sheath was used to assess the external impact of the environment on the cable.

5.2 Experimental Cables

Four basic cable designs were evaluated, as shown in Fig. 5, i.e.

1. LT cable with polyethylene (PE) sheath
2. LT cable with "wet LAP" and PE sheath
3. LT cable with "dry LAP" and PE sheath

4. LT cable with welded aluminum tube and PE sheath

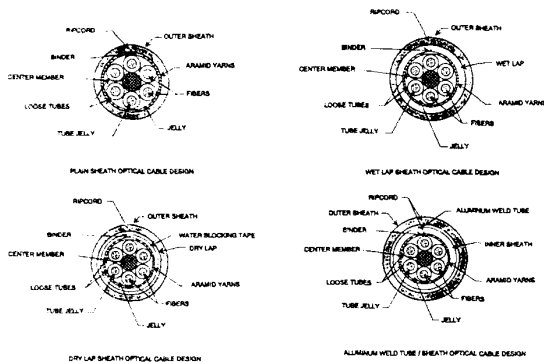


FIG. 5 DIFFERENT LOOSE TUBE OPTICAL CABLE DESIGN

The lap sheath cable utilizes a two side copolymer coated 0.008" aluminum tape longitudinally formed over the LT cable core. In the 'wet lap' version, the cable core floodant jelly is allowed to seep through the overlap of the aluminum tape. Axial water blocking is ensured, but at the expense of a good seal of the overlap. For the 'dry lap' version, a composite polyester/waterblocking tape is applied over the jelly impregnated core. This contained the jelly within the core thus improving the efficiency of the lap sealing process. The waterblocking tape then acts as a moisture barrier for any axial water flow.

During the aluminum welded tube process, an eddy current detector is used on-line to detect pinholes during the weld process. One hundred micron pinholes can be detected using this system. Any pinholes detected are filled in a second pass off-line process.

6.0 CABLE PERFORMANCE AND RELIABILITY TESTING

Two parallel test plans are used to determine the performance capabilities of the intended steam resistant cable designs.

1. First, cable manufactured with the intended tube materials must be verified to meet as a minimum the performance specifications of Bellcore TR-TSY-000020, Issue 4.
2. Secondly, the cable must exhibit high reliability in the subject steam environment.

6.1 Specification Testing

Dry Lap sheath cables housing each of the tube materials were subjected to the full Bellcore test schedule. Results are indicated in Table 4. The key result is that attenuation performance of the fibers over the -40°C to +70°C temperature range is excellent both before and after 85°C temperature aging. All mechanical test results also exceed the minimum requirements stipulated in the Bellcore document.

6.2 Cable Lifetime Test Methods

In order to simulate a pseudo steam environment, and to facilitate testing in the laboratory, a 100°C boiling water test was developed. Cable samples were inserted in a 100°C water bath with cable ends isolated from the water. Top of the water bath is covered to reduce evaporation of water. Samples were aged for the following time intervals: 1 day, 7 days, 15 days, 30 days, 60 days, 90 days respectively. At each aging time interval, cable samples are removed after aging and then examined as follows:

1. Cable is dissected at the midsection of the submerged cable length and examined for any signs of degradation in cable components.
2. The Condition of PBT tubes was evaluated for visible signs of degradation or changes in handling characteristics.
3. Melt flow index (MFI) of PBT was measured according to ASTM D1238 using Tinus Olsen Extrusion Plastometer under the following conditions:

Test Temperature: 250± 1°C

Piston Weight: 1 kg

Preheat Time : 6 minutes plugged

Test Time : 0.25 or 0.50 minutes dependent upon flow rate

Orifice : standard stainless steel

A method for sample preparation was developed for obtaining repeatable MFI results on cabled PBT tubes (8).

4. The oxidation induction time (OIT) of polyethylene sheath of the aged cable sample was measured using a DSC module of Dupont TA-9900 thermal analyzer. Testing was conducted as follows:

Sample size: 5 - 10 mg
 Container: open aluminum
 Nitrogen purge: @ 50 ml/min.
 Isothermal at ambient temperature for 5 minutes to stabilize equipment.
 Equilibrate sample at 30°C
 Ramp 20°C min.⁻¹ to 200°C
 Equilibrate @ 200°C
 Start oxygen purge: @ 50 ml/min.
 Measure time to exotherm

6.3 EXPERIMENTAL RESULTS

6.3.1 Melt Flow Index Variation

Polyester materials are well known to undergo hydrolysis reactions when subjected to high temperature and high humidity conditions (3,4). The hydrolysis reaction proceeds by scission of the main polymer chain at the ester linkage. This results in a reduction of molecular weight of the polymer and hence an increase in the melt flow index. The reduction in molecular weight also leads to a reduction in mechanical strength of the material and eventually leads to a catastrophic failure. Therefore MFI is a good aging indicator for PBT in high temperature humid environments and thus also a good indicator for moisture propagation through the outer sheaths.

We have used the value of the normalized melt flow index > 10 as a criterion to define cable lifetime. This value has been determined empirically to be indicative of the onset of cable failure, as demonstrated by increasing brittleness of PET tubes. Fig. 6 shows variation in MFI for different aging time intervals under 100°C boiling water conditions for different cable samples. From the figure, the following inferences can be made:

1. A plain sheathed PBT LT cable degrades very quickly in a harsh steam environment. Based on a 100°C boiling water test, the lifetime is expected to be only 9 days.
2. An improvement is made by using metallic sheath as a moisture barrier. However, it is obvious that the condition of the seam, or LAP overlap, plays an important role in determining the

imperviousness of the cable structure to water.

3. It is clear that by using an Aluminum welded tube to enclose the cable core a substantial increase in cable lifetime is achieved. Furthermore, up to 30 days in 100°C boiling water there is no indication of hydrolysis induced degradation in PBT.

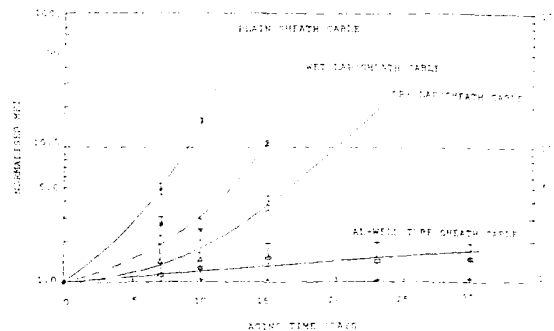


FIG. 6 MFI VARIATION FOR DIFFERENT CABLE DESIGNS.

Figures 7 and 8 show conditions of PBT tubes in both plain sheathed and aluminum welded tube cable designs for different aging times in 100°C water. There are no visible signs of degradation in PBT tubes for the Aluminum welded tube cable design.

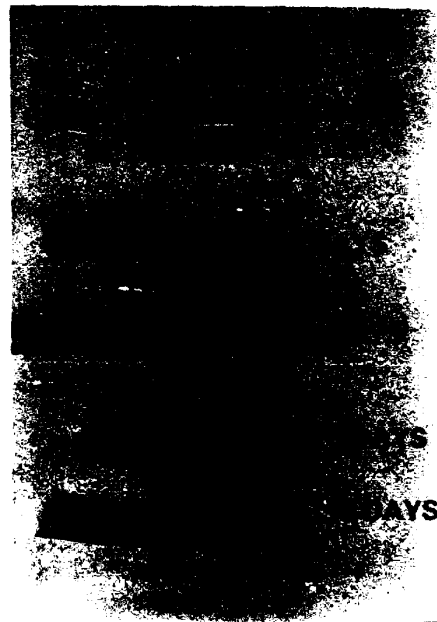


FIG 7 PHOTOGRAPH SHOWING CONDITION OF PBT TUBES IN PLAIN SHEATH CABLE

ALUMINIUM WELDED TUBE CABLE DESIGN **CONDITIONS AFTER BOILING IN 100 DEG.C WATER**

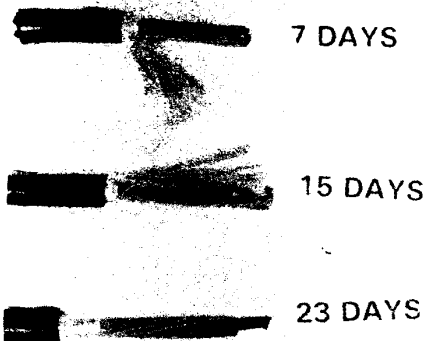


FIG.8 PHOTOGRAPH SHOWING CONDITION OF PBT TUBES IN AL' MINIMUM WELD/SHEATH CABLE.

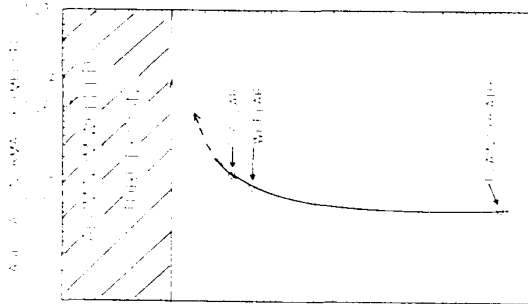
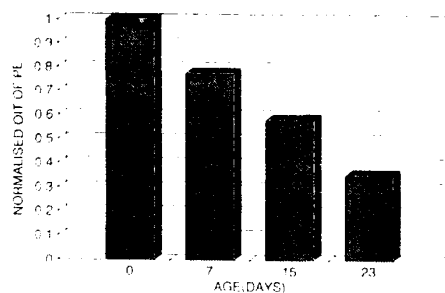


FIG.9 DESIGN CURVE FOR CABLE LIFETIME ESTIMATION

FIG.10 NORMALISED OIT VARIATION OF PE IN 100 DEG.C WATER



6.3.2 OIT Variation of Polyethylene Sheath

The effects of steam exposure are felt more by the external Polyethylene Sheath. Oxidative indication time (OIT) was measured for polyethylene sheaths of cables aged in 100°C boiling water. The OIT value is defined as the time for oxidation to begin at an elevated temperature (typically 180 - 210°C) in a pure oxygen atmosphere (5,6). The OIT value is related to the stabilizer concentration for a given material and stabilizer package (7). Fig. 10 shows the variation in OIT of Polyethylene jacket with increased aging in 100°C boiling water. This reduction in OIT corresponds to depletion of stabilizers by the high temperature. There may be some migration of the stabilizer into the cable components.

7.0 PERFORMANCE MODEL

Figure 9 shows the cable lifetime design curve for different cable designs incorporating PBT tubes. An Aluminum welded tube design has therefore a predicted long lifetime in steam conditions, estimated to at least 14-times the lifetime of a plain sheath cable. It should be emphasized here that so far we have looked at PBT degradation to iterate a cable design. It can be further shown that by using PES or E-CTFE the longevity of the cable will be further enhanced since these materials do not hydrolyze or degrade in steam conditions. A dry LAP sheath cable was manufactured using these materials and aged in the 100°C boiling water test. There is no sign of brittleness or degradation in these materials, where in the same cable PBT was disintegrating within 20 days.

From Fig. 6, it is clear that the MFI of PBT follows a relationship of the form:

$$M = M_0 \exp (\phi t) \quad \text{-- (1)}$$

where M = MFI,
 M_0 = MFI at $t = 0$
 t = aging time
 $\phi = A_0 \exp (-E_i/RT) * P^r$ expresses the Arrhenius dependence of the rate of degradation on temperature and a proposed power law dependence on the partial pressure of moisture available for reaction.

A_0 = constant

E_i = activation energy for the scission reaction

R = gas constant

T = aging temperature

P = partial pressure of water

r = power law exponent

Equation (1) yields the following equation for the rate of change of MFI under a constant temperature and external humidity condition.

$$\frac{d}{dt} \left\{ \log_e \left(\frac{M}{M_0} \right) \right\} = \phi P^r \left[1 + \left(\frac{r}{P} \right) \frac{dP}{dt} \cdot t \right] \quad \text{-- (2)}$$

where dP/dt = mass flow rate of water into the tube material.

By Fick's law

$$dP/dt = D (dc/dx) A_c \quad \text{-- (3)}$$

where D = Diffusivity of barrier layer, dc/dx = concentration gradient of water and A_c is the cross section for water flux propagation. Substituting equation (3) into (2) leads to:

$$\frac{d}{dt} \left\{ \log_e \left(\frac{M}{M_0} \right) \right\} = \phi P^r \left[1 + D A_c \left(\frac{r}{P} \right) t \frac{dc}{dx} \right] \quad \text{-- (4)}$$

Considering perpendicular flow through a uniform sheet of jacketing material into the core region,

$$\frac{dc}{dx} = \frac{C_0 - C_i(t)}{x} \quad \text{-- (5)}$$

where C_0 is the equilibrium moisture concentration in the jacket, $C_i(t)$ is the time variant moisture concentration in the core and x is the diffusion distance, i.e., jacket thickness. This equation assumes that immersed in water, the sheath reaches its equilibrium moisture concentration relatively quickly, so that $C_0(t) = C_0$ is constant. Also in the case of PE plain sheathed

cables, the moisture concentration in the core presumably reaches saturation quickly, as indicated by the MFI test results.

If we assume for the case of moisture preventative cables instead that concentration C_i in the core is very low, as for the welded aluminum sheathed cable, then $C_i(t) \ll 1$ and

$$\frac{dP}{dt} = \frac{D A_c C_0}{x} \quad \text{-- (6)}$$

$$\text{or } P(t) = \frac{D A_c C_0 t}{x} \quad \text{-- (7)}$$

By substituting equation (7) into equation (4), finally gives the equation for the rate of change of MFI as follows:

$$\frac{d}{dt} \left\{ \log_e \left(\frac{M}{M_0} \right) \right\} = \phi \left[\frac{D C_0 A_c t}{x} \right]^r [1 + r] \quad \text{-- (8)}$$

The degradation can therefore be minimized by either reducing the cross section for moisture flux, for example by using the welded aluminum sheath, or by choosing a polymer jacket material with equally low permeabilities = DC_0 . Unfortunately, polymeric materials tend to be inherently moisture permeable.

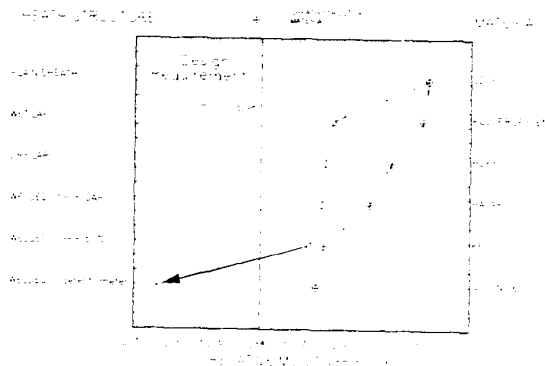


FIG. 11 DIAGRAM SHOWING RELATIVE MOISTURE FLUX FOR DIFFERENT SHEATH DESIGNS

Figure 11 shows the relative barrier strength obtained by choosing from a variety of polymers or through the use of hermetic metallic sheath, with values normalized to a non-metallic LDPE sheath. Nylon-6 is found to be one of the best choices for jacket material based on permeability, with a value of $.138 \times 10^{-13} \text{ (cm}^3 \text{ (stp) cm) / (cm}^2 \text{ s Pa)}$ (9). While almost three orders of magnitude better than PE, this level of barrier is not as good as even a poorly applied welded aluminum sheath.

For a welded aluminum sheath with an average 100µm square pinhole occurring every meter, the effective barrier is three to four orders of magnitude more effective than using a Nylon sheath with no metallic barrier. Practical experience indicates a pinhole rate of one per km level. Additionally, it is important to note that the polymer

permeabilities shown are at 25°C. Permeability increases exponentially with an activation energy with increasing temperature. Hence at steam temperatures, permeability of an optimum least permeable polymer will increase substantially thus negating its initial function as an effective moisture barrier.

8.0 CONCLUSIONS

A cable design study was undertaken to evaluate requirements for reliable operation of fiber optic cables exposed to high temperature steam environments. Two primary requirements are that the cable maintain mechanical integrity after long term aging in the environment and that the hydrolysis sensitive UV-acrylate coated optical fibers be isolated from moisture ingress.

Polyethersulfone and E-CTFE have both been shown to be suitable in terms of temperature and hydrolytic stability for use in the environment. Both materials have rated operating temperatures in excess of 140°C. PES, evaluated here for the first time for use in loose tube fiber optic cables, has exceptional mechanical characteristics and is readily processed on standard LT extrusion systems.

A model has been developed to demonstrate the effectiveness of moisture barriers in terms of polymer permeability and effective moisture flux cross section, as determined by gaps or pinholes in an applied metallic sheath. The best performance is achieved using a welded aluminum tube drawn down over the inner core. Such a sheath is expected to have diffusion rates into the fiber vicinity orders of magnitude lower than non-metallic polymer jackets.

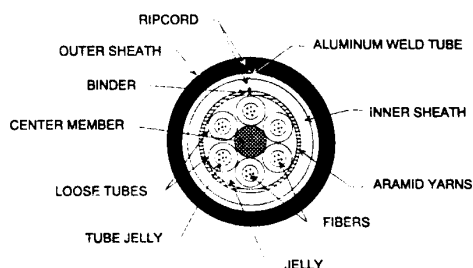


FIG12. STEAM RESISTANT OPTICAL CABLE DESIGN

This performance was verified in 100°C boiling water tests where the lifetime of PBT-tube cables under a welded aluminum sheath has an expected life approximately 14-times that of the same tubes in a plain sheath cable.

The preferred cable design shown in Figure 12 utilizes both the welded aluminum sheath and the high performance tube materials to provide the highest degree of protection for long term operation of the optical fibers in the steam environment.

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10.0 ACKNOWLEDGEMENTS

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Material Property	Standard	Units	Material A	Material B	Material C	Material D
Density	ASTM D 792	g/cc	1.78	1.37	1.68	1.31
Melt Flow Index	ASTM D1238	g/10 min.	8	11.7	3	9
Ultimate Tensile Strength	ASTM D 638	psi	5510	12200	7000	7600
Elongation at Break	ASTM D 638	%	650	40-80	200	>= 50
Flexural Modulus	ASTM D 790	psi	55000	377000	240000	300000
Crystalline Melting Point	ASTM D 696	F (° C)	273 (134)	464 (240)	464 (240)	190 (254)
Linear Expansion Coefficient	ASTM D 696	F -1	6.1×10^{-5}	5.5×10^{-5}	1×10^{-4}	1.3×10^{-4}
Water Absorption (24 hrs. @ 23°C)	ASTM D 570	%	0.04	0.7	<0.1	0.45

Table 2. Properties of New Tube (Materials)

Test	RESULTS		
	Material B	Material C	Material D
I Low Temperature Cold Bend Test (-20 C) Mandrel Size = 2.5 mm 10 Turns	No cracks or kinks	No cracks or kinks	No cracks 5 kinks
II Bend/85 C Jelly Aging After 5 days After 10 days After 15 days	No further cracks or kinks No further cracks or kinks No further cracks or kinks	No further cracks or kinks No further cracks or kinks No further cracks or kinks	No further cracks or kinks No further cracks or kinks No further cracks or kinks
III Stress Cracking (1) 150 C/Ambient Air 30 days soak (2) 170 C/Ambient Air 30 day soak	No cracks No cracks	No cracks No cracks	
IV Tube Compression Compressive Modulus (N/mm) Yield Load (N)	5496 1002	3296 827	5359 1354
V Tube Shrinkage 120 C/24 hours	1.2%	2.8%	0.5%

Table 3. Tube Material Reliability Data

Test Item	Specification Requirement	Dry LAP Cable	Dry LAP Cable
Temperature Cycling -40 C to +70 C	All attenuation measurements at 1.55 um. (1) <= 0.20 dB/km maximum loss increase. (2) <= 0.10 dB/km mean loss increase. (3) 80% fibers <= 0.1 dB/km at 2nd -40 C.	All polyethersulphone tubes (1) <= 0.10 dB/km maximum loss increase. (2) <= 0.05 dB/km mean loss increase. (3) Pass	E-CTFE and PBT Tubes (1) 0.028 dB/km mean loss - mat. C tube 0.046 dB/km mean loss - PBT tube (2) Pass
Temperature Aging	(1) <= 0.4 dB/km maximum loss increase. (2) <= 0.20 dB/km mean loss increase. (3) 80% fibers <= 0.20 dB/km at 2nd -40 C.	Pass Pass Pass	Pass Pass Pass
Long Tensile and Bend Test	<= 0.10 dB loss at 600 lbs.	<= 0.05 dB loss	0.06 dB - Mat. C tube < 0.04 dB - PBT tube
Compression Test	<= 0.10 dB loss increase at 2200N load. No increase at release.	0.03 dB loss change for load up to 4.4 KN.	0.01 dB change in mat. C & D tubes at 2.2 KN.
Impact Test	<= 0.20 dB @ 4 kg load	2 samples at 6 kg - pass 0.02 dB change no damage to any cable components	0.01 dB change at up to 6 kg. no damage to any cable components
Flex. Test	<= 0.10 dB change at x 20 cable O.D. mandrel size	x 17 mandrel 0.02 dB change	x 25 mandrel - no damage; or attenuation change with 6 kg.
Twist Test	<= 0.10 dB change	0.02 dB change No damage to sheath or tubes	0.03 dB change No damage to sheath or tubes

Table 4. Experimental Cables: Specification Testing Data