Protection of Silica Based Fiber Optics in a High Moisture Environment

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Abstract

For fiber optic cables used in a high moisture environment such as long-term subsea submersion, the phenomenon of micro-crack propagation is a well-known issue leading to increased attenuation and ultimately optical discontinuity. The fatigue factor, *n*, of a fiber is a quantification of its robustness and resistance to microcracking. Fatigue factor can be strongly affected by buffering and cable jacketing.

One method used to protect silica from moisture is to deposit carbon directly onto the silica during the draw process and immediately prior to buffering. Carbon deposition will protect against moisture ingress but inherently weakens the silica. Other methods include waterblocking tape wrap included at some point in the cable jacket layering or fillers surrounding the fiber that are resistant to moisture.

Another method of moisture protection is to employ a cable jacket made from a material that provides high hermeticity. In this paper we will discuss this method and its advantages in long-term subsea deployment.

1. Introduction

Fiber optics has become a ubiquitous part of our daily lives and is largely responsible for delivering many of the modern conveniences to which we have become accustomed: 99% of the data for our phone, internet and television are transmitted via cables.

Data transmission via a fiber optic cable is achieved through pulses of light and is conducted through a silica glass in the core of the cable. Despite the silica glass being very delicate, itself, fiber optic cables are being increasingly deployed in harsh environments that range from space, to oil & gas down hole drilling to the deepest trenches of the ocean. Cable strength and reliability is achieved through buffers and jackets over the fiber that protect the silica and enable this otherwise delicate photon conduit to be deployed in the harshest environments on earth and beyond.

Subsea cables may be exposed to corrosion, moisture, high pressure, high forces in the axial and lateral directions, high temperatures and assaults from various sea creatures. To perform well in these environments one needs a cable jacket that will protect the glass from many or all of these conditions. One way to do this is to give the glass a strong primary buffer. In many fiber optic cables, the silica based core and cladding are protected initially with a carbon layer. This is deposited during the draw process and prior to the buffer layer. The function of carbon is to provide protection from moisture. We will discuss the function of carbon and its drawbacks in more detail below.

Ideally it would be advantageous to use a standard COTS telecom grade fiber that has an acrylate primary buffer. This will be incorporated into a fiber optic cable and then can either be used by itself or become a component of a larger umbilical that may include other fiber, copper cables, strength members and armoring. However, acrylate is a highly absorptive material and if moisture makes its way through the jacket of the fiber optic cable, it will undoubtedly be absorbed by the acrylate buffer, which can cause a change in the optical performance of the fiber.

If one intends to deploy a fiber optic cable alone (not in an umbilical configuration), the necessity to ruggedize the fiber is quite obvious. The way one goes about protecting this fiber is not equally as obvious. The properties required to safeguard against all these harsh conditions are often contradictory. Typically weight is a byproduct of strength, yet weight becomes a major system handicap if long lengths are to be deployed. High tensile strength and flexibility also are usually mutually exclusive. And perhaps the most important correlative properties are a high level of protection and cost.

2. Optical Fiber Failure

Whereas mechanical reliability of the optical fiber itself is of paramount importance for long-term communications reliability, there has been extensive industry study on the dynamic and static fatigue of fiber. Fiber fatigue is a function of propagation of micro cracks in the silica which are induced and accelerated by the presence of moisture. Stress corrosion is a reaction of the silica bonds with water that results in the cleavage of the Si-O-Si bonds.[1]

In practice, the weakest defects are removed by proof testing the fiber to some stress level, σ_p.[2] However, any defects that remain after proof testing are vulnerable to stress corrosion.

The industry standard method for measuring fatigue factor is described in FOTP-28 "Measuring Dynamic Strength and Fatigue Parameters of Optical Fibers by Tension". In this test a 0.5m gage length is used and fibers are tensile tested at different strain rates. The weakest site, or largest flaw, within a specimen will fail and the typical failure stress decreases as the gage length increases.[3]

Because a hermetic coating layer essentially prevents the introduction of water to the surface of the glass to preclude sub-critical crack growth (fatigue), hermetic fibers can operate at a higher operating stress level than non-hermetic fibers. It is generally accepted that standard non-hermetic fiber can be used at an operating stress up to 25% of the initial prooftest level; however, since hermetic fibers show little appreciable crack growth over a lifetime, they can operate up to 80% of the original prooftest level.[4]

3. Moisture Barrier Properties of LCP Coated Optical Cable

One of the primary functions of the optical fiber coating is to prevent the ingress of water vapor, as the strength of the optical fiber deteriorates rapidly in the presence of moisture due to stress corrosion. All polymers are permeable to water to some degree. The permeability is given by the product of the moisture diffusion coefficient D, and the solubility S, and is defined as the mass of water transmitted per unit area per unit time per unit of pressure for a given thickness of the polymer. Liquid Crystal Polymers, LCPs, because of their rigid crystalline molecular orientation, exhibit the lowest levels of moisture permeability of any polymer. The relative permeability of Vectra A950 LCP and a variety of other commonly used polymers is shown in Figure 1.

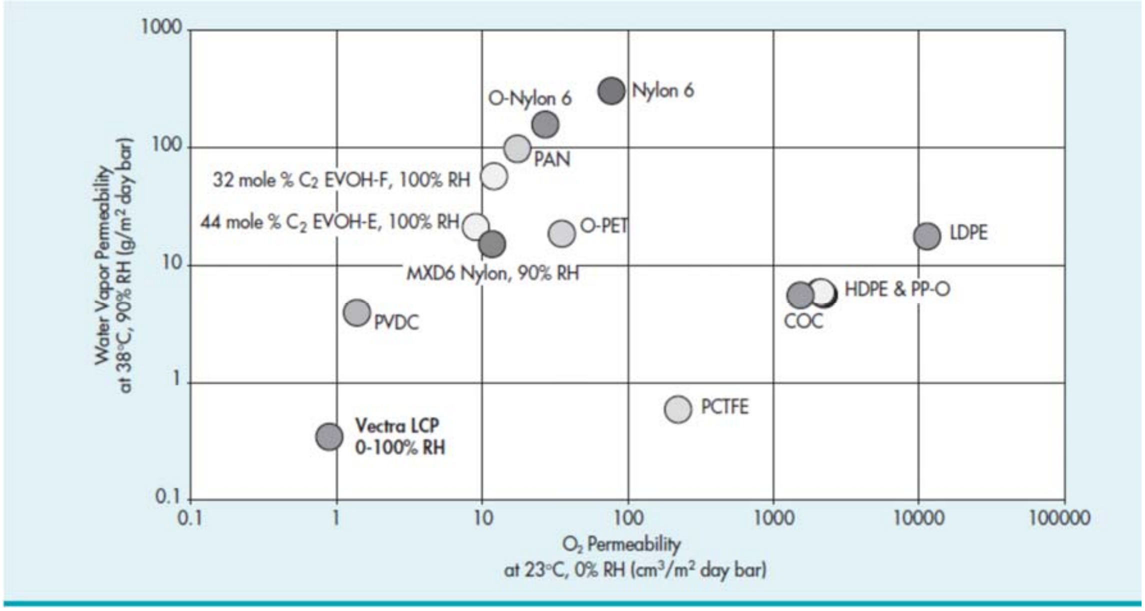

Figure 1. Permeability of various polymer films (25 µm thickness)

Figure 2 compares the moisture absorption of standard Corning SMF28e fiber and Linden's Liquid Crystal Polymer (LCP) coated SMF28e fiber and shows just how much moisture can be absorbed by an unprotected fiber. In this experiment we exposed a 5m length of bare fiber to 100% humidity at 23°C. Within 30 minutes it has saturated and absorbed 7.5 mg of moisture. When it is protected by a jacket which is impervious to moisture, in this case LCP, it is still unsaturated after 340 hours at 70°C and 100% humidity.

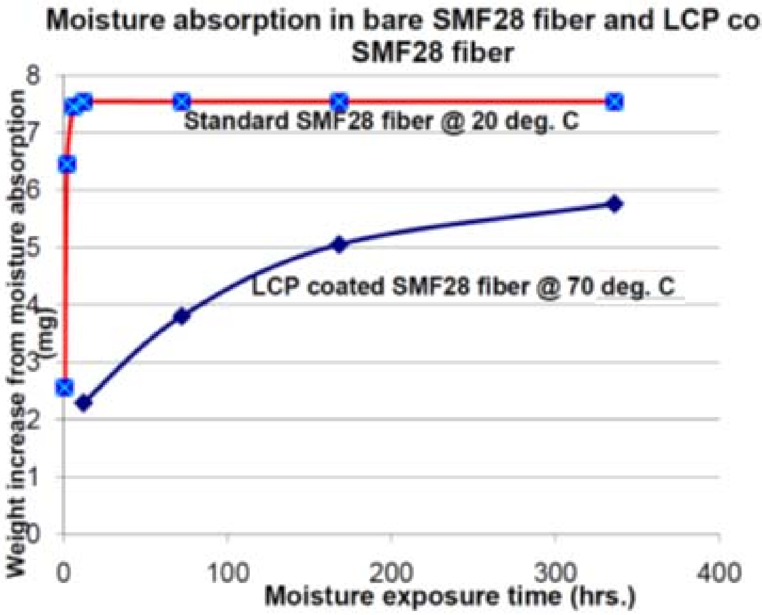

Figure 2. Moisture Absorption vs. Time in LCP Buffered SMF28e Fiber Cable

4. Carbon vs. LCP Coated STFOC

As part of a Navy funded developmental program, Linden Photonics performed a fatigue factor test as follows: Two fibers were submerged in water @ 80° C. Fiber one was a bare fiber with hermetic carbon coating and fiber two was a bare OFS Allwave Flex fiber with acrylate buffer, jacketed with LCP. These fibers were each wound around two different coils – 1 inch and 6 inches in diameter. Fibers on the 1” diameter mandrel would have high levels of static stress and the fibers on the 6” to have very little static stress. One (1) inch diameter corresponds to 50 kpsi stress on fiber, while 6 inch represents near zero stress on the fiber. Fibers were removed from the water bath after 1, 2, 3, 4, 7, 11, 17, 28, 45, 72, 116, 187 and 300 days. The tensile strengths of the samples removed were tested on the tensile tester shown in Figure 3 below.[5]

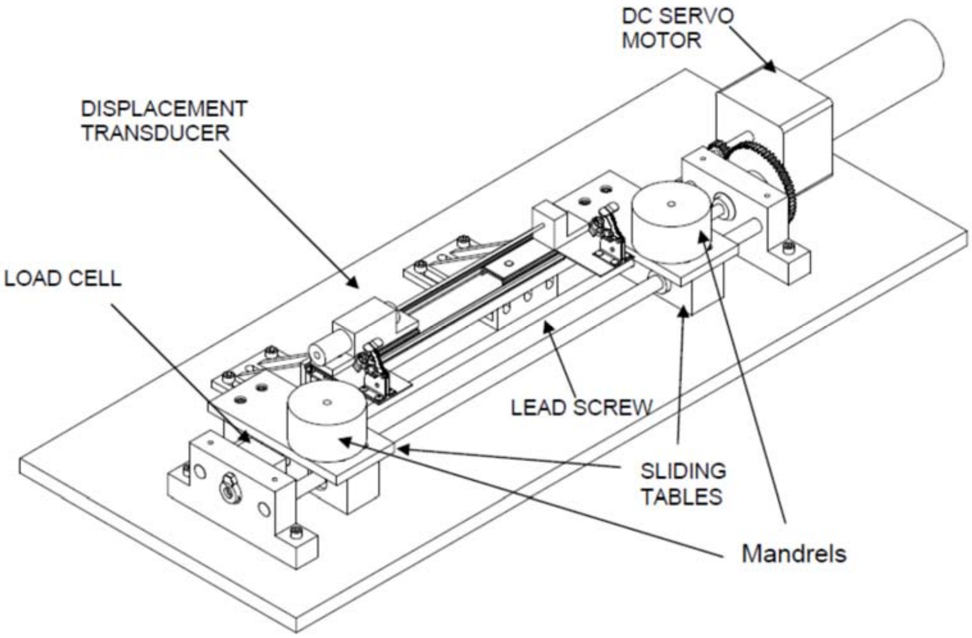

Figure 3. Linden Photonics Tensile Tester

Results of the Highly Accelerated Stress Test (HAST) can be seen below in Figures 4 & 5. At each point during this test, the bare Allwave fiber protected by LCP outperforms the carbon coated fiber.

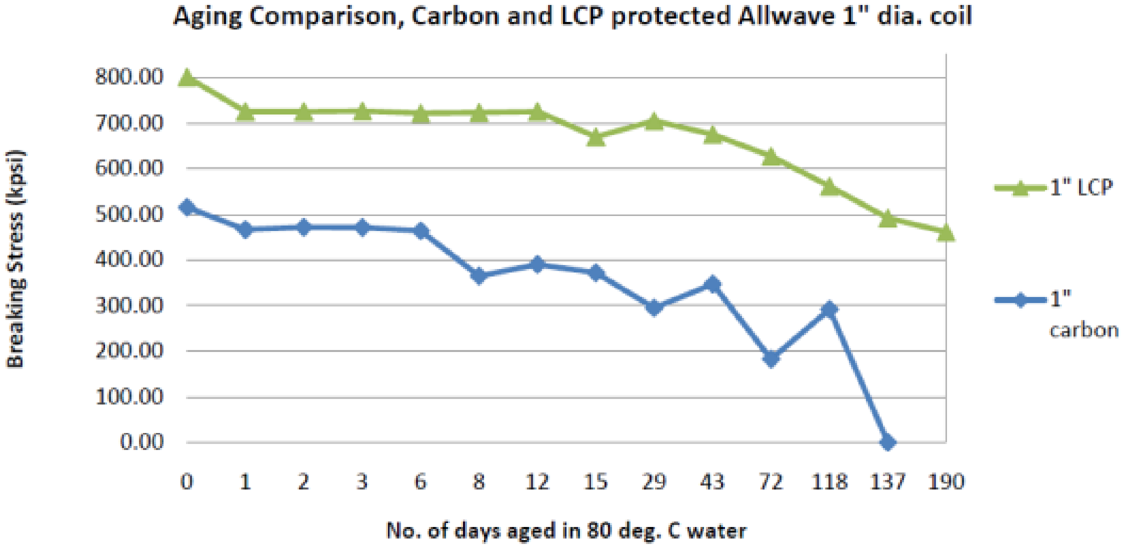

Figure 4. Aging Comparison Graph for Carbon and LCP Protected Allwave 1" Diameter Coil

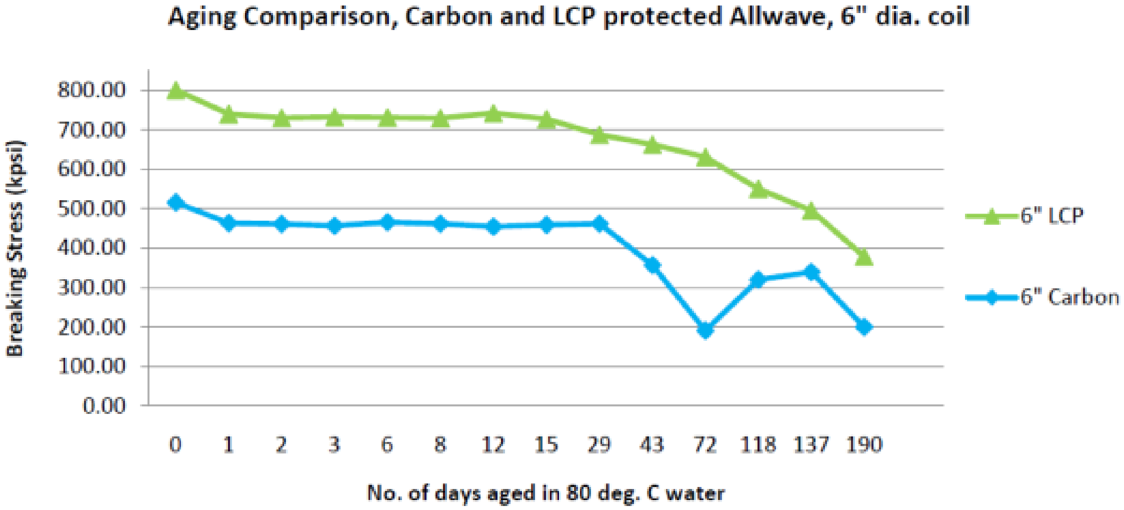

Figure 5. Aging Comparison Graph for Carbon and LCP Protected Allwave 6" Diameter Coil

Carbon is used as a hermetic coating for silica fiber to prevent moisture from reaching the silica and reducing tensile strength over time. However, the process of applying a carbon coating to silica itself reduces the tensile strength of fiber by 30-40%. This is why in both Figures 4 and 5 above, the carbon coated fiber starts the test at a lower value than fiber which is protected with LCP.

In Figure 4 the line for carbon fiber drops precipitously to zero at the 137 day mark. This is due to the fact that the fiber protected with carbon on the 1" mandrel became so saturated with moisture that cracking occurred along the entire length of the fiber. The fiber was so brittle that not one single length sufficient for tensile testing could be obtained. The fiber on the 1" mandrel after many days immersed in water is shown below in Figure 6.

Figure 6. Carbon Fiber Sample with Breaks Along Length

5. Alternative Cable Waterproofing Methods

5.1 One method to waterproof cables with multiple internal elements is to wrap them in a water resistant tape. This tape wrap can have multiple functions such as binding the elements in place to prevent movement during flexing and twisting of the cable while deployed. A Linden Photonics cable is shown below in Figure 7. This cable has a multi-layer wrap providing several functions; waterproofing, electrical conductivity, and mechanical stability.

Figure 7. Linden Photonics Hybrid Cable with Tape Wrap

There are two layers of tape wrap shown in Figure 7. The metallic tape on the right side of the picture is an aluminum/polyester tape that provides conductivity for cable drain wires and serves as water blocking. The white tape on the left side of Figure 7 is a polyester tape is wrapped contra helically to the aluminum-Mylar tape and provides added stability and additional water blocking. While Mylar has very low moisture permeability as compared with other polymers, it is still many times that of LCPs. Mylar Polyester film will absorb roughly 0.8% moisture when immersed in water for 24 hours,[6] LCPs have a moisture equilibrium content of 0.02% to 0.04%.[7]

Another factor to consider about tape wrap as a method of waterproofing is the fact that the tape is applied in an over lapping manner around the inner elements and as such has periodic joints along the entire length of the cable which are areas of increased moisture permeability. LCP jacketed cables will have a continuous jacket that is free of pin-holes. This continuous jacket provides no weak areas as does a tape wrapped moisture barrier.

While tape wrapping is a commonly used method to limit moisture ingress in cables, it is a slow manufacturing process and most processes will have a maximum line speed of 50 feet per minute, while extrusion, the method used to apply LCP jacketing will run at speeds from 400 to 500+ feet per minute.

The polyester wrap is an impregnated cloth that will swell when it comes in contact with water. This is designed to prevent any water from entering the center of the cable should the outside jacket develop a hole or tear. These tape wraps are called dry-waterblocking.

5.2 Wet waterblocking is a gel that fills in spaces in the center of a cable and provides a higher level of water blocking than tape alone. However gels are messy to work with and unlike tapes that can be simply cut off for termination, waterblocking gel can make clean up an issue especially when terminating fiber optic cables whereas the fiber optic connector ends must remain clean.

While both of these waterblocking methods are helpful for prolonging the life of a cable they are not considered hermetic and as such will not offer as much improvement to fiber optic cable fatigue factor as a hermetic layer like carbon or, preferably, LCP.

5.3 Placing a fiber or multiple fibers in a metal tube is another way to protect fiber from the elements including moisture and while this is an effective method to protect from moisture, metal tubes are not flexible. The recommended bend radius of steel tubes are on the order of feet, while polymer based jackets can be used with a bend radius of inches.

Figure 8. LCP Jacketed Non-Kink™ STFOC™

Another drawback of using fiber in a metal tube is weight. Stainless Steel 316 has a density of 7.99 g/cm^3 as compared to LCP which is 1.4 g/cm^3. Weight is a big concern for subsea cables, especially when buoyancy is critical as is typically the case for ROV tethers.

5.4 The most common industry standard for fiber optic cables calls out a requirement for water penetration as follows: "When a 1-meter static head or equivalent continuous pressure is applied at one end of a 1-meter length of *unaged* cable for 24 hours, no water shall leak through the open cable end."[8]

Cables for subsea use will see higher pressures and are tested accordingly. However, most tests are geared towards large long submarine power cables. One such standard is Electra 189-2000 published by Cigre – International Council on Large Electrical Systems.

Working depth, pressure, overall cable construction and type of subsea usage all need to be considered when determining the necessary protection needed for fiber optic elements within.

6. Conclusions

The subsea environment is a harsh one for cables, especially ones containing silica based fiber optic elements. Among the many forces at work against cables including marine life, pressure and wave action, one as seemingly benign as moisture ingress can ultimately have catastrophic consequences on a cable's performance and length of service.

One way to improve the length of service of a cable used underwater is to protect the underlying fiber from moisture. In other words, and as discussed above, to improve the fatigue factor of the fiber optic element. This can be done in many ways and at varying levels of protection. In the most extreme cases, or where long service life is desired, a near hermetic level of protection must be employed.

We have discussed several methods of moisture protection ranging from tape wrap, gel filling, metal tube enclosure to the more hermetic methods of carbon deposition and finally LCP jacketing. LCP has been shown to be better than carbon in terms of moisture protection and it also allows for low cost, fast manufacturing. And as opposed to carbon the use of LCP does not have an initial impact on strength of fiber. If using single channel fiber cable alone, this is a recommended method for proper protection of fiber. Even in umbilicals moisture ingress can occur. LCPs are a low cost, low weight, highly flexible method to extend cable life.

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