Submarine Communications Cable for Deep-Sea Application

Gary Waterworth,
Alcatel, Optical Networks Division
Christchurch Way
Greenwich, London SE10 0AG, UK
gary.waterworth@asn.alcatel.co.uk

Ian Watson
Alcatel, Optical Networks Division
Christchurch Way
Greenwich, London SE10 0AG, UK
ian.watson@asn.alcatel.co.uk

***Abstract*-This paper details the design and qualification of high reliability submarine cables specifically developed for the telecommunications industry. These cables are now readily available to support various offshore applications where multi low loss optical fibers and medium voltage power is required. The paper covers the design requirements specific to submarine application, such as pressure, water and gaseous ingress and installation requirements. The range of cable types available and their characteristics are covered together with the description of specific design elements that are utilized, optical fiber, optical package, strength member, insulation, water blocking, armoring and hydrogen protection. The extensive qualification programs already undertaken are also briefly covered. Connectivity between various types of submarine cable and submerged equipment is also a by-product of the telecommunications industry that is well established. An example of a high strength bend restrictor and deep-water cable penetrator already qualified with the cable is given.**

I. INTRODUCTION

A. Historical Background

In 1843 Dr Montgomerie discovered the special properties of gutta–percha, an extract from the Malaysian heva tree. Two years later Silver and Faraday invented a process of insulating copper wires with this new engineering material. This enabled a British company; later to become the Telegraph Construction and Maintenance (Telcon), to manufacture the first submarine telegraph cable for the Brett brothers in 1850, connecting England and France [1].

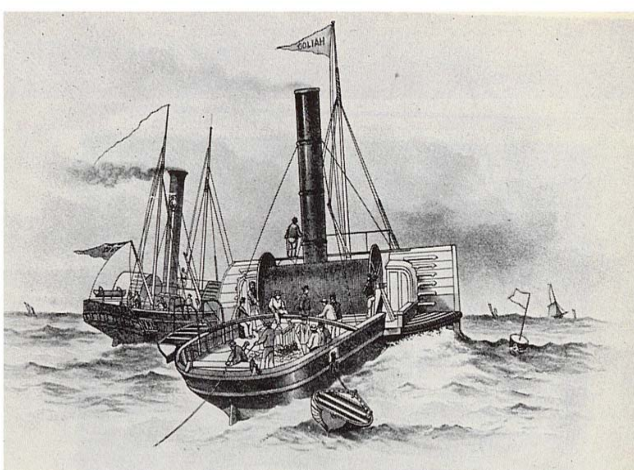

Fig. 1.Goliath laying the first cross-channel cable escorted by HM Surveying Paddle Ship Widgeon.

Telcon manufactured and installed a further 680,000 km of submarine telegraph cables, before another invention lead to the introduction of co-axial submarine telephone cables [2]. In 1933, a research program on chemical reactions at high pressure inadvertently produced a solid high-molecular-weight polymer [3]. By 1936 the inventing company, Imperial Chemical Industries (ICI) had a development team looking at suitable applications for this easy to mould material with excellent insulation properties. B Habggod of ICI and J Dean of Telcon both recognized the potential application for submarine telephone cables, so in 1938 Telcon ordered 100 tons of Polythene, now normally referred to as polyethylene [4]. Another new development, the radar, took precedence at the outbreak of WW2, delaying the first deployment of polyethylene insulated telephone cables until 1945. The last major milestone in the very long history of submarine cables has its roots back in 1966 when two scientists, Kao and Hockman, working for STC at the laboratories in Harlow, England reported that they had found a possible replacement to co-axial cables with a higher capacity and lower material cost. It took another 19 years before optical fiber was first utilized in a commercial submarine system.

B. Development of High Reliability products

There are, of course, many other important milestones in the long history of the development of today's telecom submarine cables. The three mentioned above help to demonstrate how important the telecom industry has been as the main driving force behind submarine cable development. With the exception of the relatively more recent high voltage and umbilical cables, the submarine cable industry's main customers have traditionally been the major telecom operators. Many of the standard principles used today in the design of all submarine cables are based on the early work of telecom cable engineers such as Zajac [5] and Roden [6]. The commercial benefit of connecting North America to Europe and Asia has resulted in the availability of high reliability multi fiber optic medium voltage cable that can be deployed and recovered in water depths beyond 8000m. The consumer demands for high quality and very high availability have been passed on to the engineers developing, manufacturing and qualifying the telecom submarine cables. Telecom products have therefore been designed, manufactured and qualified to the most exacting standards of the national carriers from Asia, Europe and America.

C. Today's market climate

The early 1980's saw all the major national carriers in Europe, Japan and the United States starting work on developing fiber optic submarine cables with the first transatlantic system commissioned in 1988. During the 1990's approximately 20 submarine telecom systems where installed per year. Deregulation of the telecom market, the advent of the Internet and the high initial profits by some new carriers, all factored into the explosion of interest in submarine telecom systems between 1997 and 2001. During this 'bubble' in 2000, 4 transpacific and 3 transatlantic systems were commissioned, where previously the average was les than one. Most submarine telecom cable suppliers increased both capacity and productivity. The bubble burst in 2001 leaving the products and manufacturing capacity largely intact.

D. Non-telecom application

Field proven, high reliability submarine communication cables are now readily available for non-telecom projects. They can be equipped with a wide variety of fiber types, provide power to submerged equipment. Manufactured and shipped in either short or very long lengths, designed for either shallow or deep water, these specialist cables are able to meet many new non-telecom project requirements. As it is normal practice in submarine communication systems, all these cables have proven and qualified couplings and penetrators for connection to underwater equipment. These can be readily adapted to interface with a wide range of sub sea equipment that is based on designs with more than ten thousand cumulative operating years without a failure.

II. DESIGN REQUIREMENTS

A. Submarine Communication Cable

A good submarine communications cable should provide a long service life of 25 years or more, with stable optical and electrical performance. It should be easy to joint and maintain at sea if necessary. In order to provide stable performance it must survive both the rigors of installation and the environmental conditions on the seabed. Installation in both shallow and deep water imparts tension and torsion on the cable structure, which houses the optical fibers and electrical conductor and insulation. Longevity of the installed cable depends on minimizing the strain induced on the cabled fiber. The environmental conditions such as hydrostatic pressure, abrasion, crush and hydrogen must be accounted for. The cost of developing and qualifying a submarine communications cable to meet these requirements with a very low failure rate is extremely high and is normally amortized over many thousands of km of cable. The extensive development costs for the cables developed for the telecom industry are historic and therefore non-reoccurring. Moreover, the cables have been sea trialed and proven with more than 100,000km of product in the field.

B. Cost of poor reliability

It has been correctly reported that the cost of a submarine cable repair at sea can cost as much as 500,000USD[7]. Why should a cable fail or its performance degrade? Most reported submarine cable failures are due to external aggression [8]. This can be further partitioned into 'Human Activity' and 'Natural Aggression'. Fishing is the major worldwide cause of damage, more than 50% of reported repairs, nearly all in shallow water of less than 500m. Anchors, both for mooring and for fishing cause 20% of the failures. 15% of repairs are due to natural causes such as chafing, abrasion or earth movement. It is standard practice to attempt wherever possible to separate the cable from the hazard. Careful route planning and burial is applied where circumstances allow. Often the only option open to the route planner is to surface lay all or part of the system. Partial burial is common due to insufficient depth or stability of the seabed soil / sand. Burial is by far the best protection, however it is not without its premium and the reliability of well-buried cables depends on the intrinsic failure rate of the cable itself. The reliability of surface laid cables depends additionally on the crush resistance of the cable design.

Fig. 2 Damaged shallow water cable after contact with fishing tackle

III. SUBMARINE ENVIRONMENTAL CONSIDERATIONS

A. Fiber Sensitivity to Hydrogen

It has been well known for long time that silica based optical glass fiber is sensitive to hydrogen. Several mechanisms can generate hydrogen in a submarine environment. Galvanic or magneto hydrodynamic corrosion of the cable's external armoring, polymer degradation and metallic out gassing of the cable's internal structure, and marine biology can all play a part in generation this adverse condition [9]. It is also common that powering designs require sea earths that can generate hydrogen where the sea is used as a low resistance DC path [10]. Hydrogen can dissolve interstitially into the fiber, straining the crystalline structure, it can form hydroxyl groups and form defect centers, all resulting in an increase in optical attenuation. This increase in attenuation can result in an unrecoverable signal quality requiring complete cable replacement. Fibers intended for submarine application can be manufactured with tighter controls on contamination and halogen content reducing the effect hydrogen has on the fiber's optical loss. Special fibers of this type are widely available at a small premium. This fiber enhancement is not however sufficient on its own to avoid large increase in optical attenuation. All submarine communication cables therefore employ various methods to protect the fiber from the several atmospheres of hydrogen partial pressure. The main method employed in all successful designs is to provide a hermetic barrier fabricated by forming and welding a metallic tape into a tube surrounding the fiber.

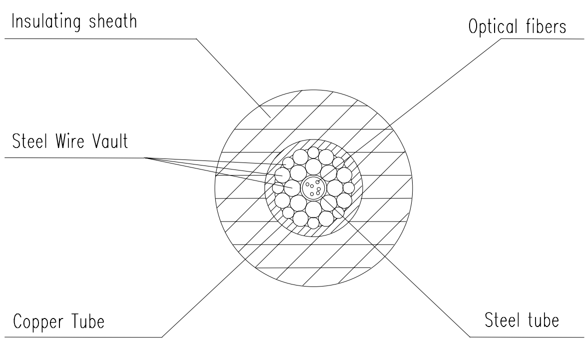

Fig.3 .Typical deepwater cable cross section showing the internal hydrogen barriers and steel vault.

B. Reparability

Another key consideration in the design of submarine cable is to ensure that it is readily repairable at sea. As mentioned above, repair is normally only required if the cable is hit by trawling equipment or anchors. Some cable designs can survive this type of damage better than others. This is especially relevant to submarine cables required to supply power to submerged equipment. Here the cable design must protect both the fiber package and the insulation. Some cable designs have been recently enhanced to provide better protection to the insulation layer against crush loading [11]. If however the cable is damaged and requires repair, it is important to limit the internal axial ingress of seawater. High hydrostatic pressures can force water many kms along the cable unless it is effectively blocked. The cost in replacing the 'wet' cable in terms of materials, ships time and system outage can be very high without good water blocking. Some repairs have taken days longer than expected where this important requirement has been overlooked. When two 'dry', cable ends are onboard ready to join together, a fast, reliable and readily available process is often preferable to a supplier proprietary technique. Four submarine telecom cable suppliers and a marine installation and maintenance service provider form the 'Universal Jointing (UJ) Consortium' which offers qualified and proven jointing techniques for a wide range and combinations of cable types [12]. The choice between a Universal Joint and a proprietary method can be made based on the service agreement and service supplier envisaged. There are however, options with telecom cables as most have been qualified by the Universal Joint Consortium and many vessels around the world are equipped and trained for the Universal Joint.

IV. SUBMARINE CABLE DESIGN

There are many types of submarine communication cables available. The design structure varies depending on manufacturer, fiber count and powering requirements. Each type however comes with different external protection packages. Fig 4 shows a typical range of cables used to supply 200kW of power and 24 optical fibers.

Fig.4 *.Range of medium voltage telecommunication cables from deepwater on the right to shallow water on the left*

A. Light Weight (LW)

These cables not twist excessively under load and have a low weight per meter, making them best suited for deep-water. Typically used for areas with flat seabed and low currents, in water deeper than 2500m.

B. Lightweight Protected (LWP)

Here a metallic tape, steel being preferred for the additional abrasion protection despite its higher density, protects the insulation. it can be deployed down to 7000m and is often used in areas of abrasion risk, such as slopes and high currents. It is also used in shallow water, where conditions allow for good burial.

C. Single Armour Light (SAL)

A single layer of small (<4mm) diameter wires protects the insulation and optical package. This cable type is normally used where the cable can be successfully protected by burial. Due to the twisting limitation on most armored cables, the depth is normally limited to 2000m.

D. Single Armored Heavy (SAH)

Similar in construction to the Single Armored Light, but with heavier (~5mm) wires to provide additional protection. This cable is normally used in shallow water and where full burial protection cannot be guaranteed. The additional weight limits the deployment depth to about 1500m.

E. Double Armored Heavy(DAH)

Two layers of wires protect the insulation and optical package, both laid in the same direction (Left Hand). This cable has the highest level of tensile strength, but also the highest weight per meter. This cable is used where the greatest level of protection is required. This is typically a) where the cable cannot be buried at all due to sea bed geology, pipe or cable crossings, b) in very shallow water where the risk of anchors damage is present (<80m) or c) for shore ends where the cable is floated ashore or pulled through directionally drilled pipes. A variant called 'Rock Armour' with a shorter outer amour layer pitch is sometimes used where a higher level of crush resistance or better conformance to an uneven seabed is required.

V. SUBMARINE CABLE QUALIFICATION

Extensive qualification or type testing is conducted on submarine telecom cables [13], normally in accordance with international standards [14]. The complete armor range and joints between the armor types is thoroughly tested. The tests typically include:

A. Tensile Test Under Free Gyration

The cable is loaded with its ends free to rotate at its Nominal Transient Tensile Strength (NTTS), the maximum safe load the cable can withstand for up to one hour without reducing the reliability of the optical fiber. The cables optical performance is monitored and its elongation under load and after load is measured.

B. Combined Tensile Test Under Fixed and Free Gyration

Cable and joints are loaded up to the NTTS and then the cable's Normal Operating Tensile Strength (NOTS), the maximum safe load the cable can withstand for up to 48 hours without reducing the reliability of the optical fiber. Optical monitoring and elongation are checked. This test is made on two samples, one with the ends fixed and the other with the ends free to rotate. The Joints are further tested to ensure they meet the insulation requirements and cable's Ultimate Tensile Strength (UTS).

C. Long Length Tensile Test

Several hundreds of meters of inner cable structure are loaded up to the corresponding strain of the cable at the NTTS and NOTS, while it is optically monitored.

D. Hydrostatic Pressure Test

A long length of cable, up to 1000m is pressurized to sea bottom pressures while the optical fibers are monitored. Joints, which normally have a larger diameter than the cable, are also tested with shorter cable lengths.

E. Aging

Several kms of cable is held at a temperature higher than the maximum operating and storage temperature for two months with the fiber optical performance monitored.

F. Long Term High Voltage

The cable is submitted to an accelerated voltage test in water for 6 months that equates to 25 years operation.

G. Crush Testing

Loads up to 150kN are applied over a loading surface 100mm long. The cable optical and electrical performance is tested during and after the crush loading.

H. Water Ingress

Long lengths of cable up to 1000m with an open end are installed inside a pressure vessel and are suddenly subjected to full sea bottom water pressure. The cable is removed and dissected to find the maximum distance that water has penetrated internally.

I. Round the Sheave

Cable and joints under a tensile load equal to the cable's NTTS are passed several times around a 3-meter diameter wheel or sheave while optically monitored.

J. Corrosion

Cable and joints are placed in heated, flowing water for several months while the hydrogen content of the joints internal atmosphere is monitored.

K. Interlayer Adherence

The cable is loaded to its NTTS and NOTS for one hour and 48 hours respectively, with one end fixed via an external cable stopper. A similar test is often carried out during a sea trial with the cable handling equipment. Slippage is monitored and a post test high voltage check is carried out.

Temperature cycling, impact, abrasion, minimum bend, shock, vibration and specific electrical tests are also conducted before a cable can be considered as qualified.

VI. CONNECTIVITY TO SUBMERGED EQUIPMENT

A. Cable to Equipment Interface

The interface between telecom sea cable and submerged plant and equipment is complex. Not only must the connection provide load transfer through what is a discontinuity in the cable but it must also maintain electrical insulation whilst supporting the safe interconnectivity of both optical fibers and electrical conductors. Telecom systems often require the use of submerged repeaters or amplifiers spliced into the cable at regular intervals of between 40 and 100km [15]. The design utilized by Alcatel is described here further.

B. *Typical Telecom Repeater to Cable Coupling*

The connection to the telecom sea cable is undertaken within an Extremity Box (EB), representing effectively one half of a cable-to-cable joint and is located at either end of the submerged plant (see Fig. 5).

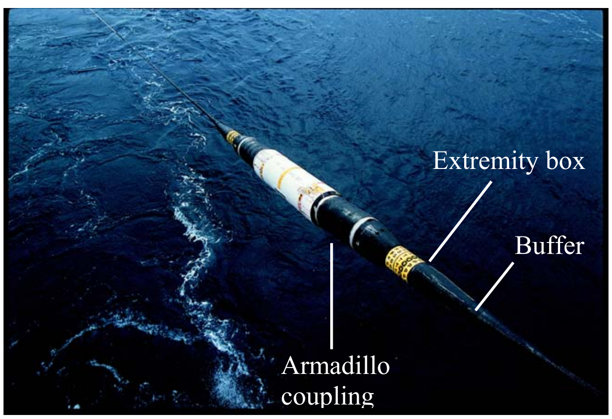

Fig 5 Repeater being laid at sea

The internal make up of the Extremity Box is comprised of a stainless steel hydrostatic pressure and tensile load bearing housing having cable vault anchorages at either end for effective termination of the cable strand wire and inner fiber tube. Located between the anchorages is the splicing box where fiber interconnections between the wet plant and cable are stored. The integrity of electrical insulation of medium voltage cables is maintained by over-molding the entire assembly [16]. Once over molded the extremity box housing is located within a glass filament wound sleeve. This sleeve provides protection for the insulation from external damage in addition to providing both an anchorage for armor wires and means of load transfer between the cable and articulated coupling attached to the submerged equipment. In this instance armor wires are splayed within a conical seating within the sleeve and are prevented from extraction under tension by filling the cavity with an epoxy resin encapsulation (see Fig. 6).

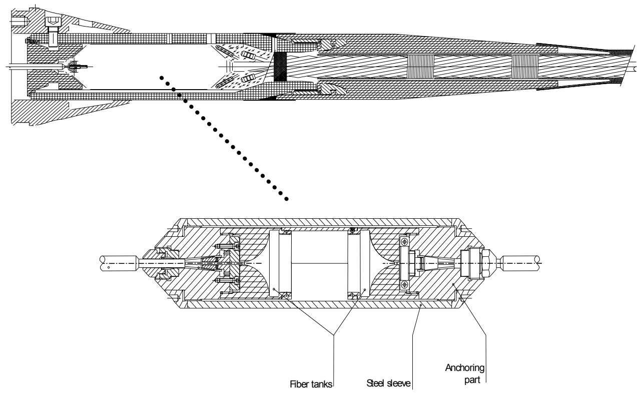

Fig 6 Typical extremity box with armor wire anchorage

C Armadillo

The load chain is maintained between the Extremity Box glass reinforced sleeve and the main housing of the submerged plant by the presence of an articulated interface called an "Armadillo", so called due to its likeness to the plated coat of the insect eating mammal of the same name.
The Armadillo type of coupling has been used for many years and is a successful, long established and versatile design. The unit comprises of a series of high strength angular faced plates linked by Spherically seated high strength bolts (see Fig. 7).

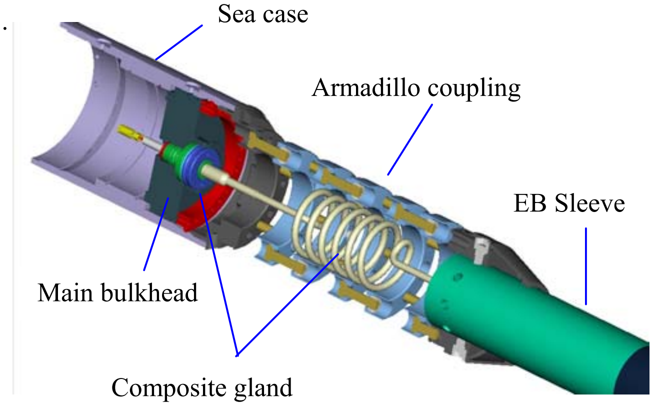

Fig. 7 Submerged equipment coupling and gland interface

Such an arrangement allows up to 90 degrees of articulation depending on the number of plates selected and can support loads of over 60 tonnes in straight tension and 20 tonnes articulated. Anchorage of the unit is by direct coupling to the sea case via a threaded base plate whilst the sleeve of the termination is accommodated within the nose cone of the coupling.
Such a robust coupling design is essential as during the deployment and recovery, the weight of the cable and submerged plant in suspension passes through the repeater and couplings. In addition, the housing length can magnify the inboard cable tension as it passes over cable drums or sheaves.

D Composite Gland

Optical and electrical interconnection between the sea cable extremity box and the main equipment housing is provided by a unique penetrator design, called the composite gland.

The composite gland is essentially a combined electrical and optical feed through which provides the only means of access in or out of the deep-water amplifier. The gland not only has to provide insulation against system line voltages as the housing and bulkhead into which it is located is at earth potential, but must also prevent water and hydrogen gas penetration whilst supporting a benign environment for up to 26 optical fibers to pass through. As the gland is located inside of the amplifier cable coupling, its physical geometry must also provide for the extension, compression and flexural movement of the coupling whilst exposed to hydrostatic pressures at depths of up to 8 km.

The single penetration composite gland is mounted within the main bulkhead at each end of the equipment sea case. Both units are hydraulically sealed using o-rings and hermetically sealed using a pressure activated lead shear seal.

The gland itself comprises of long water-blocked tube, which acts as both the electrical conductor and fiber carrier. Over voltage insulation of up to 36kV is provided by the adoption a ceramic sleeve that is bonded to the conductor using a ceramic to metal seal. A polyethylene sheath on the tube and further overmoulding on the gland housing provide continuity of the cable and Extremity Box insulation.

The fibers themselves are sealed within the assembly using a cocktail of proprietary resins and the carrier tube filled with a blocking material, which displays low permeation to hydrogen. As the gas leakage performance of the gland is proportional to the bore diameter of the tube and inversely proportional to its length the gland is not only coiled for compliance within the coupling, but is tuned to meet the hermeticity requirement for the submerged plant. The combination of both gland and bulkhead sealing technologies provides a typical hermeticity performance of better than 1 x 10 –7 cc/s at 5 MPa.

The resulting overall package of interconnection technology described above, provides a robust, reliable and highly efficient system that is readily adaptable to other similar deep-sea applications.

VII. CONCLUSION

Many years of development by the telecom industry has produced a wide range of cost effective submarine communication cables with associated joints and connectivity. These cables can support high fiber counts up to 96 fibers, power distribution to at least 200kW and depths of more than 8000m. All are well tested and field proven, and readily available for demanding non-telecom applications. Higher reliability is often commercially beneficial in the longer term, reducing operational expenditure. Careful choice of the cable type and cable protection is of paramount importance in the planning of a successful project.

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