Development, Testing and Track Record of Fiber-Optic, Wet-Mate, Connectors

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Abstract

Underwater-mateable fiber-optic connectors enable subsea system designers to build modular subsea components and systems utilizing high-speed and long-distance optical communication systems that can be assembled underwater. The optical connectors enable connections and disconnections of optical systems underwater, providing connectivity for: installation and maintenance purposes; for future system expansion; for the latest strategic optical sensor technologies or as part of installed underwater optical communication hubs. In anticipation of the demanding operating environments these connectors have been qualified to the highest and most rigorous standards. This presentation provides an overview of the qualification testing completed plus a summary of the track record, of underwater-mateable, fiber-optic connector suitable for use in extreme operating environments.

1. Introduction

Underwater optical fiber and communication systems have been in use in the oceanographic, subsea oil and gas and defense industries for many years now. The main advantages of such systems are well known, for example:

- Significant increase in communication bandwidth and speed of data transfer
- Significant increase in communication distances
- Immunity to electrical noise
- Well-known temperature dependant properties of optical fiber

The use of wet-mate optical connectors, enabling modular underwater installations, combined with the advantages above, have allowed a significant growth of the following:

- Increasing quantity, speed and sophistication of remote, distant underwater monitoring and control
- Significantly longer transmission distances
- Real-time performance assessment
- Real-time health and status monitoring of subsea equipment for safety and to better understand equipment maintenance regimes
- Greater opportunity to access large quantities of raw subsea data
- The use of high power transmission systems which rule out conventional electrical data communications due to Electro Magnetic Interference (EMI)

It is the advent of these newer technologies moving into the subsea environs and in deeper waters that have created not only the need for optical wet-mateable connector products but also the number and increasing diversity of them as well.

2. The Challenge

As a very brief introduction to fiber optical communications, the principle of operation exploits the ability of light to travel efficiently within a very fine glass fiber. The glass fiber is essentially an optical wave-guide in which light stays trapped within the core by near total internal reflection between the core and it's outer cladding. The core consists of a 9µm diameter high refractive index glass material covered by a 125µm diameter lower refractive index cladding. For comparison of size, a human hair is 90µm diameter. The 125µm cladding may also be covered in a protective coating to a diameter of 250µm that subsequently may also be covered by a secondary coating, or buffer, to 0.9mm.

The main challenges of wet-mate fiber optic connector design and manufacture are:

- The alignment and coupling of these very fine 9µm diameter glass fiber cores, underwater, without any contamination across the optical faces nor degradation of optical performance
- The ability to operate underwater for long periods of time without discernable degradation

Figure 1 – ROV HydraLight

3. Specifications

The increasing demand for optical applications has allowed the growth in quantity and availability of optical system products. These in turn affect the customer's requirement for optical wet-mateable connectors. These varied technical and commercial requirements include but are not limited to those examples identified in Table 1. These points all have an impact on product design, development, cost, qualification and availability. In each case these requirements are assessed for compatibility with current products in an attempt to standardize product elements. In many cases there are technical, physical or commercial constraints that require alternative solutions, especially when the quantities are significant and the costs can be justified. Over the last few years this increasing trend from customers has led to the development of a family of several different wet-mateable optical products. This has allowed more technical and commercial choice of field proven products for the end-user.

Parameter	Specifications
Lifetime	• Long term (25 years plus), • Short term (months only)
Optical Losses	• As low as possible (≤ 0.5dB) • ≤ 2dB
Size	• As small as possible • Don't care
Cost	• Must be inexpensive • Don't care but not exorbitant
Material	• Non-corrosive metal body materials • Non-metallic body materials
Configuration	• ROV, AUV, Diver, Stab-plate
ROV Handle	• T-bar, H-handle, Fishtail-handle • ISO 13628-8
Temperature	• Low or high temperature only • Wide operational temperature
Channels	• Single channel • Up to 8 channels • As many as possible
Termination	• Cable, hose termination • Strength member termination
Testing	• Fit for purpose • Extensive test program, extremes • Destructive

Table 1 – Customer Specifications

4. Optical Wet-Mate Connectors

These requirements have led to the development of a range of optical wet-mateable connectors as shown in Table 2:

Connector	Description
HydraStar	• 8-channel electro/optical
HydraLight	• 8-channel optical, military version • 8-channel optical, ROV version
MicroStar	• 4-channel optical only slim-line connector
S-Series	• 4-channel optical only, modular optics
Photon	• 4-channel electro/optical, modular electrics and optics

Table 2 – Optical Wet-Mate Connectors

5. HydraStar Wet-Mate Electro/Optical Connector

5.1 Introduction

The 8-channel HydraStar is the backbone of the wet-mate optical connector product range. It is a hybrid (electro/optical) connector that has proven itself as a rugged and reliable design. Following the successful conclusion of a very rigorous qualification test program, the HydraStar now has an impressive accumulation of field data over the last 6 years.

The HydraStar connector, as a hybrid, offers a combination of up to 8 electrical and/or optical circuits with a high degree of integrity. Whilst it has been used mostly for combined electrical and optical applications, it is also ideal for pure optical applications. The connector is simple with few moving parts and offers robust operational and optical performance.

The connector underwent significant and rigorous testing with emphasis on the original criteria regarding the challenges of fiber-optic wet-mate connectors i.e. the alignment and coupling of these very fine 9μm diameter glass fiber cores underwater without any contamination across the optical faces, without high optical losses and to operate underwater for long periods of time without discernable degradation. These points were easily confirmed by extensive testing and backed up by subsequent experience in the field. Figure 2 shows both halves of a HydraStar set.

Figure 2 – HydraStar

5.2 Qualification Testing

The testing included the following:

1. **Optical Parameters.**

   Insertion Loss (IL) is the light power lost through the connection. The average optical attenuation measured during qualification was -0.28dB with a standard deviation of 0.06dB.

2. **Electrical Parameters**

   Insulation Resistance measures the 'quality' of insulation between each electrical contact element and any other adjacent conducting element. The test target was >1Gigohm (10^9ohms) and in all cases the electrical IR measured exceeded this. Contact Resistance measures the resistance through each connector electrical contact. In all cases the measured contact resistance was less than the design parameter of 0.1ohm.

3. **Deep Ocean Environment Pressure Cycling.**

   The test chamber used filtered natural seawater held at a temperature of 32°-35°F (0°-1.6°C) during the pressure cycling between 0psi and 10,000psi (0bar to 690bar). Test connectors were cycled hundreds of times at various test pressures and pressure cycling.

4. **Sand/Silt Testing.**

   Extensive mating/de-mating testing of the connectors inside a turbid sand, silt and seawater environment was completed. This verified the ability of the two front connector seals to prevent particulate contamination from entering the connector and prevent internal pressure compensation fluid from escaping. As the connectors are pressure compensated these tests were also successfully repeated with a 15psi (~1bar) overpressure inside both connector halves and again with a vacuum in both halves to verify that even with pressure differentials the seals work as designed with no evidence of leakage.

5. **Low Temperature Testing.**

   The connectors were also subjected to low temperature testing to verify the low temperature capability of the two front connector seals. The connector is rated operationally down to 32°F (0°C) with a comfortable margin.

6. **Inter-mateability.**

   During all testing of connector sets, the inter-mateability of each connector half with all other available connector halves was conducted. In all cases the average optical attenuation was in the order of -0.3dB. The connectors are therefore specified and rated independent of connector pairing.

The majority of this testing was conducted at the Naval Facilities Engineering Service Center (NFESC) in Port Hueneme, California in October 1998. Additional testing by other third parties to further qualify and evaluate the connector has included hyperbaric testing, pressure cycling, shock testing and vibration testing.

5.3 Track Record

Current reliability information is based on actual field data. A statistical analysis of the field data confirms the product's operational performance in the field. Only connectors delivered and either taking part in system integrations or operating in the field have been included within this information but the accumulated operating time is in excess of 3.2 million hours with a calculated MTBF of better than 900,000 hours, with a 99% confidence level. As the track record of this product progresses in the many different applications it is used in, so too does the confidence in meeting the challenge "to operate for long periods of time underwater without discernable degradation" and consequently in selecting it for use underwater and especially for long-term deepwater applications. The HydraStar has now been used successfully to 9,900 feet (3,017m).

6. HydraLight Wet-Mate Optical Connector

6.1 Introduction

The first such derivative of the HydraStar was the smaller HydraLight. Direct customer advice was the catalyst that led to the development. The HydraLight is basically a 2nd-Generation optical only HydraStar that incorporated the following additions:

- Smaller size
- Improved optical performance
- Addition of plug cover sleeve
- Stronger springs and enclosure of main springs
- Seawater compatible interior
- Standardized Omnitec MKII PBOF hose interface
- Improved chemical compatibility
- Improved compensation fluid

There are two versions of the HydraLight:

- Military stab-plate version
- ROV version

Both of these utilize identical operating principles and technical specifications to that of HydraStar. The military version being part of host sub-system for underwater Defense applications and the ROV version being the direct optical-only HydraStar replacement for long-term and deepwater applications.

Figure 3 – ROV HydraLight Receptacle

6.2 Technical Changes

Removal of the electrics to make this an optical-only connector led to an immediate size reduction and the addition of a cover sleeve around the plug was incorporated. Enclosure of the receptacle spring was achieved efficiently within the ROV version. In addition the compensation oil and elastomers used were re-evaluated with the final findings indicating positive reasons for change. It was therefore decided to design and qualify the connector with the same synthetic compensation oil as used in the HydraStar. Similarly the elastomers were also changed to a compound of fluorosilicone, which has proved to be a robust alternative with a greater degree of compatibility with the types of chemicals used in the oil and gas industry.

Additionally the ROV version was designed with a seawater compatible interior. This was driven by a specific customer with a requirement to ensure in the unlikely event that the HydraLight became flooded; it would remain functional for a long period of time. Figure 3 shows an ROV HydraLight receptacle half.

6.3 Testing

The qualification testing of the HydraLight has been extensive and rigorous, covered by two separate test programs, one for the stab-plate version for military use and the other ROV version.

1. Military Stab-Plate Version.

The testing was conducted by third party personnel at Southwest Research Laboratories in San Antonio, Texas and as well as optical testing, included; over 440 mate/de-mate cycles in total; mate/de-mate cycles in clean seawater to 9,800 feet (2,987m); mate/de-mate cycles in sand/silt seawater. In all cases the testing showed good connector optical and mechanical performance within specifications throughout. Figure 4 shows the military stab-plate version.

Figure 4 – HydraLight - Stab-Plate Version

2. ROV Version.

The extensive test program was conducted by SEA CON® personnel at a variety of locations including: Southwest Research Laboratories in San Antonio, Texas; NTL, Lockheed Martin and SEA CON®. The test program included:

(a) Optical Performance

Optical attenuation measurements were performed at 1310nm and 1550nm wavelengths, in both directions. A sample of over 4000 test measurements yielded the following results:

- Mean optical attenuation: -0.2dB
- Single standard deviation: 0.1dB

Optical back-reflection measurements were performed at 1310nm and 1550nm wavelengths and in both directions.

A sample of over 4000 test measurements yielded the following results:

- Mean optical back-reflection: -50dB
- Single standard deviation: 4dB

On the HydraLight, no observable optical cross talk could be measured on any other optical fiber within the connector of the active light optical fiber.

(b) Optical Performance Longevity

The connectors were subjected to an extended set of testing to verify the optical performance is maintained versus the number of mate cycles. In all cases the optical insertion loss remained better than –0.5dB and optical back-reflection better than –45dB. This test was also successfully repeated during the coldwater, turbid, sand and silt testing to further verify optical performance longevity in potential extreme operating conditions.

(c) 24 hours Helium Leak Test on Seals

The critical end-seals were subject to and qualified to meet a full 24-hour leak test using Helium.

(d) Seal Vacuum Integrity Test

Similarly the end-seals were subject to a seal test in the reverse direction using an internal vacuum.

(e) Maximum Misalignment Tests

This test verified no damage and correct operation and optical performance of the connector at specified worst-case misalignments during mating operations. These were:

- Rotational ±10º
- Angular ±5º
- Radial ±0.25”

(f) Locking Device Test

This test verified the ability of the connector to latch, lock, and then unlatch successfully. It was conducted with a simulated snag of 2,500N (562 lbs) on the hose assembly in both the axial and 45° positions.

(g) 5,000N ROV Force Test

This test simulated an applied ROV force on the connector in the axial direction and verified no damage. The force verified was 5,000 N (1124 lbs or 510kg).

(h) Mating Force Tests

This test measured the mating and de-mating forces under dry (in-air) and wet (in water) conditions. In all cases, no damage was recorded or observed to either connector and the results were:

- Engagement Force: <622N (140lbs)
- Disengagement Force: <222N (50lbs)

(i) Turbid Tank Tests

The test connectors were mated a total of over 650 times in cold 0°C and 4.5°C (32ºF to 40ºF) turbid sand, silt and seawater at ambient pressure and at 10,000psi. The tank was continuously agitated to ensure the solids remained in suspension and the test was repeated 3 times with the connector in horizontal, vertical and 40º inclination positions.

Over 2,700 measurements yielded:

- Average insertion loss: -0.1dB
- Average back-reflection: -48.8dB

(j) Mechanical Shock

The connector was subject to a shock of 30g for 11ms in the x, y and z planes.

(k) Vibration

The connector was subject to a double-sweep vibration profile on each of the x, y and z planes, including optical performance monitoring: Displacement: 5 Hz to 25 Hz ± 2 mm and Acceleration: 25 Hz to 150 Hz, 5g

(l) Thermal shock

The thermal shock tests were conducted to verify that the connector can survive realistic thermal shocks whilst in operation, each repeated 3 times:

- High temperature – Temperature raised to 158°F (70°C) and allowed to stabilize for 4 hours, then rapidly cooled by immersion into a cold ice/water bath held at 32°F to 40°F (0°C and 4.5°C).
- Low temperature – Temperature lowered to -40°F (-40°C) and allowed to stabilize for 4 hours, then rapidly brought to ambient by immersion into a cold ice/water bath held at 32°F to 40°F (0°C and 4.5°C).

(m) Extended mate/de-mate cycles

Completed extended mate cycle to 160 mates, to assess and confirm optical performance longevity versus mate cycle. The tests were repeated in the turbid sand and silt tests.

(n) Wet-Mate Test

- Ambient, cold, freshwater - The connector was mated over two hundred times in ambient and cold 0°C and 4.5°C (32ºF to 40ºF) fresh water at ambient pressure
- Ambient, cold, turbid, seawater - The connector was mated over a hundred times in cold (0°C and 4.5°C) turbid sand, silt and seawater at ambient pressure

(o) Partial Wet-Mate Test

The test verified no damage and the optical performance of the connector remained within specification by mate/de-mating connector partially (at differing levels of completion) a total of 20 times within a turbid sand and silt environment.

(p) Hydrostatic Testing

The connector hydrostatically tested to the equivalent of 7,000 meters (23,000 feet).

(q) Compensation-Oil Loss/Water Ingress Evaluation

Additional testing was performed to quantify and verify any oil-loss during the life cycle of a connector. This testing was repeated on several connector pairs, each in excess of 100 mate cycles, in the factory, both dry and wet and repeated as part of the three turbid, sand and silt tests.

(r) Cold Mate/De-Mate Test

The HydraLight uses elastomer seals in critical sealing areas so the purpose of this test was to verify seal integrity at low operating temperatures. The temperature of the test tank was held at 32°F to 40°F (0°C and 4.5°C) and in all cases, the seal integrity was maintained and optical performance was excellent. This was repeated 3 times, with over 100 mate cycles completed during each session.

(s) Cold Mate/De-Mate Test at 10,000psi

The HydraLight uses elastomer seals in critical sealing areas so the purpose of this test was to verify seal integrity at low operating temperatures and high operating pressures. The temperature of the test tank was held at 32°F to 40°F (0°C and 4.5°C) and the tank pressurized to 10,000psi (690 bar) and in all cases the seal integrity was maintained and optical performance was excellent.

(t) Sliding Sleeve Integrity

It is important for the connector halves to seal before movement and opening of the connectors during the mating process. The connector moving parts were fully instrumented with position indicators to verify position of each connector half moving surfaces during mating and de-mating. In all cases connector integrity was maintained under the following conditions:

- Slow speeds to fast speeds
- Worst-case sleeve offsets
- Worst case connector misalignment

(u) Worst-Case Misalignments

This test verified the correct operation of connector coarse physical alignment, at forced misalignments of the mating faces and surfaces, within the connector. The design capability was verified by:

- Connector functionality
- Connector internally pressurized with gas during offset mate/de-mate cycling and verifying no seal breaches.
- Instrumented and monitored moving sleeve travel during offset mate/de-mate cycling.

(v) Flex-Tube Bending Capabilities

The flex-tubes are the flexible steel tubes within the plug connector. They are held down under the plug sliding sleeve and during mating as the sleeve pushes back by the other sealed connector half, the flex-tubes splay out into their naturally straight position, before coupling to the optical ferrules in the other connector half. It is critical that they do not deform. The design capability was verified by:

- FEA analysis
- Physically bending in excess of requirements without deformation
- Cold temperature testing

(w) Mate/De-Mate Speed Tests

The connector moving parts were fully instrumented with position indicators to verify the integrity of sealing of moving parts, quantify any internal pressure build-up due to the sliding action and quantify the maximum mate/de-mate speeds for connector mating and de-mating. The results confirmed:

- A low (non-accumulative) internal pressure peak during mating
- Mate/de-mate speeds of 12" per second verified.

(x) Oil Selection & Verification

The selection of the compensation oil for the HydraLight was based on extensive testing of the previous generation HydraStar and the initial prototype HydraLights, which changed from Silicone Oil to Synthetic Mineral Oil with the following advantages.

- Improved lubrication – Verified by testing
- Improved dielectric strength – Verified by testing
- Improved water absorption properties – Verified by testing
- Improved bulk modulus

(y) Oil Cleanliness

It is well known that the optical properties of optical contacts are susceptible to degradation due to the effects of particulate contamination. Early in the development of the HydraLight, a complete oil filtering and flushing system was developed and verified for use with the HydraLight. The resulting set-up was verified as having a direct and improved effect on optical performance.

Further to this, additional testing was conducted to qualify the hose, hose termination and jumper assemblies as being suitable for use with optical fiber and an external Fiber Management System. These were completed by Bennex Omnitec in Norway and included:

(a) Hose and hose termination

Environmental stress tests - Hose absorption/compensation, ozone resistance, ultraviolet resistance and thermal shock. Destructive testing - Tensile failure, burst pressure, crush resistance, outer sheath abrasion and hose kink testing

(b) Jumper assembly

Oscillating jumper test, jumper pull test, drop test, jumper handling simulation test, Simulated deployment test

6.4 Track Record

Both versions of the HydraLight are now installed in the field with a total of 165 units ordered. The HydraLights in the field total an accumulated operating hours of over 900,000 million hours and based on no actual field failures to date, this yields an MTBF of better than 300,000 hours with a 80% confidence level.

7.0 MicroStar Wet-Mate Optical Connector

The second such derivative of the HydraStar was the smaller MicroStar, shown in Figure 5. Direct requirements of the end-users were the catalyst that led to this development, however this involved a different and unique set of primary design constraints and subsequent issues as follows:

- Smaller size than both the HydraStar and HydraLight - 4-channel optical only, space constraints of 1.8” diameter and new internal materials and techniques
- Higher temperature rating 121°C (250ºF) – Elastomers, compensation and expansion
- Chemical compatibility – Elastomers, fluids
- Subsea-tree/tubing-hangar interfaces including - Space constraints, stack-up tolerances, keying, installation, securing, compliance, sealing, mate/de-mate, lifecycle, water-venting

Figure 5 – MicroStar Connector Set

The MicroStar is basically a downsized optical only HydraStar/HydraLight that incorporated the lessons learned from the HydraStar and design improvements learned during the HydraLight development. The operating principle and key technical specifications of the MicroStar are identical to that of the HydraStar and HydraLight.

Prototype testing has been successfully completed and qualification testing is in progress. Initial testing has confirmed the basic principles of the design and initially verified by the following:

- Optical testing - Insertion loss and back reflection
- Mechanical - Helium leak testing and mate/de-mate testing

After successful conclusion of the basic testing the connector will be issued to a third party for qualification whereby they will be simulating actual operating and interface conditions to verify that the connector remains within specification.

8.0 Photon Wet-Mate Optical Connector

Specific customer requirements wanted less expensive, smaller and lower specification wet-mate optical connectors with customer studies indicating unit cost was a major factor in connector selection.

The Photon connector, shown in figure 6 is a different concept connector altogether, compared to the HydraStar. It draws on over 39 years of experience in underwater-mateable connector design and over 10 years specifically in underwater optical connector design. The Photon is a patented modular concept device and can be easily configured from a single channel device through to any number of channels. The upper limit would be determined by the practicality of handling such a device. In addition to optical modularity, the Photon has been designed to fit the standard modular CM2000 electrical contacts to make a hybrid electro/optical connector.

The prototype designed and built is a 4-channel device with the following specifications:

- Small, similar to electrical connector size
- Average optical insertion loss of –0.5dB with a single standard deviation of 0.25dB
- Mate/de-mate cycles of less than 25
- Qualified to 1,000m (3,200feet)

Prototype testing and qualification testing has been successfully completed. This included verification of the basic principles of the design and was verified by:

- Optical testing - Insertion loss and back reflection
- Mechanical - Mate/de-mate testing
- Hyperbaric testing
- Sand-silt testing

Figure 6 – 4-Channel Photon Set

After successful conclusion of the basic testing the connector was issued to an independent third party to perform additional testing, including a statistical analysis of the insertion loss over about a dozen connector sets. The testing involved over 400 mate cycles in both wet and dry conditions and the connectors performed very well.

9.0 S-Series Wet-Mate Electro/Optical Connector

The S-Series is the latest optical wet-mate connector currently under development. Shown in figure 7, it was developed to fulfil a requirement for a small connector similar in size to the Photon but to a higher specification. It is a patented modular concept device and can be easily configured from a single channel device through to any number of channels. The upper limit would be determined by the practicality of handling such a device.

The prototype designed and built is a 4-channel device with the following specifications:

- Small, similar to electrical connector size
- Additional sealing integrity
- Average optical insertion loss of –0.5dB with a single standard deviation of 0.25dB
- Mate/de-mate cycles of less than 50
- Qualified to 1,000m (3,200feet)

Figure 7 – S-4 Optical Wet-Mateable

10.0 Summary

Table 3 summarizes the connectors in terms of relative cost, relative performance and relative lifecycle, demonstrating a conclusive coverage from low to high:

Optical Connector	Relative Cost	Relative Optical Performance	Relative Mate Cycles
HydraLight	High	Highest	Highest
HydraStar	Medium-High	High	High
MicroStar	Medium	High	Medium
S-Series	Medium-Low	Medium	Medium
Photon	Low	Medium	Medium-Low

Table 3 – Relative Cost, Performance and Lifecycle

11.0 Conclusion

Whilst an ultimate desire is for product standardization, we have responded to immediate needs by evolving and developing three wet-mateable optical connector products from the same family; the HydraStar, the MicroStar and the HydraLight plus the development of a new family of less expensive and smaller, but lower specification products, the S-Series and Photon. Also highlighted are the key elements identifying the relativity of these to; cost, performance and mate cycle.

The requirement for underwater mateable optical connectors has grown considerably over the last few years and in combination with a fast growing and successful track record, is ensuring an increase in the quantity and quality of qualified components available for use within the underwater environs for long periods of time.

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