Development, Testing and Track Record of Multi-Way Underwater- Mateable Fiber-Optic Connectors for Deepwater Applications

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Abstract

Subsea optical connectors enable the industry to build modular subsea components and systems utilizing optical communication systems. These modular systems can thus be assembled on the seafloor, the optical connectors enabling connections and disconnections for installation and maintenance purposes or for future system expansion.

In anticipation of the future ultra deepwater applications requiring the large bandwidth, high speed and long step-out distances achievable from using optical communication systems, optical wet-mate connectors have been qualified for use to 23,000 feet (7,000m) and so far been used to over 9,900 feet (3,017m).

This paper presents an overview of the lessons learned in the design, development and testing, plus a summary of the track record, of a full range of underwater-mateable fiber-optic connectors. This has enabled underwater-mateable fiber-optic connectors to join the subsea industry's selection of proven components for deepwater and ultra-deepwater applications.

1. Subsea Optical Communication Systems

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

- Significant increase in communication bandwidth
- Significant increase in speed of data transfer
- Significant increase in communication distances
- Immunity to electrical noise
- Potential cost reduction in subsea umbilical construction and installation by enabling the manufacture of smaller diameter umbilicals
- Well-known temperature dependant properties of optical fiber

It is however the use of wet-mate optical connectors that has enabled modular underwater installation and this combined with the advantages above have allowed a significant growth in the following:

- Increasing quantity, speed and sophistication of remote, distant underwater monitoring and control
- Significantly faster underwater seismic streamer array processing
- Next generation subsea Christmas tree and manifold systems
- Subsea separation, subsea processing and subsea production boosting systems

- Significantly longer step-out distances for remote well locations or subsea satellites
- Real-time assessment of reservoir performance and optimization
- 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)
- The opening up of long distance (200km) shore to field opportunities

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 of Wet-Mate Fiber Optic Connectors

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 to 900µm.

Table 1 identifies the main challenges of wet-mate fiber optic connector design and manufacture.

Number	Challenge
1	The alignment and coupling of these very fine 9µm diameter glass fibers underwater without any contamination across the optical faces
2	The alignment and coupling of these very fine 9µm diameter glass fibers underwater without high optical losses
3	The ability to operate underwater for long periods of time underwater without discernable degradation

Table 1 – The Challenges of Fiber-Optic Wet-Mate Connectors

3. Specifications for Optical Wet-Mate Connectors

The demand for optical applications is increasing and not only are the quantity of optical system products increasing but so too is the variety and complexity of the many and varied applications required. 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 extremes identified in Table 2. These points all have an impact on product design, development, cost, qualification and availability:

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
Configuration	• ROV, AUV, Diver, Stab-plate
Material	• Non-corrosive metal body materials • Non-metallic body materials
ROV Handle	• T-bar, H-handle, Fishtail-handle • ISO 13628-8 Design & Operation of ROV Interfaces on subsea production systems
Temperature	• Low temperature only • High temperature only • Wide operational temperature
Channels	• Single channel only • Between 4 and 8 channels • As many as possible
Termination	• Cable termination • Hose termination • Strength member termination
Testing	• Fit for purpose • Extensive test program to meet operational requirements • Test to extremes

Table 2 – Diversity of Customer Requirements

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 that are proving very successful.

This has resulted in the availability of this range of products, thus allowing more technical and commercial choice of field proven products for the end-user.

These requirements are increasing in both numbers and variety and with it wet-mate optical connectors are already being used on the following systems, which we know of:

<u>Oil & Gas</u>

- Qualification & evaluation programs
- Subsea control systems
  - Norsk Hydro Troll pilot project
  - Burullus Scarab/Saffron project
  - Norsk Hydro Fram Vest project

        - Phillips Little Dotty project
        - Petrobras SBMS multiphase pump project
    - Downhole instrumentation - Shell ETAP project
    - Seabed seismic system - BP East Foinhaven project
    - Deepwater drilling systems

Oceanographic Research

- ANTARES Project - subsea optical telescope, in the Mediterranean, designed for the detection of Neutrinos

Military

- Qualification & evaluation programs
- Classified Defense projects

4. Optical Wet-Mate Connectors

These requirements have led to the development of the following range of optical wet-mateable connectors:

- **HydraStar**
    - 8-channel electro/optical - Qualified
    - 14-channel electro/optical - Prototype
- **HydraLight**
    - 8-channel optical, military version - Qualified
    - 8-channel optical, ROV version - Qualified
- **MicroStar**
    - 4-channel optical only connector for tree/wellhead applications - Prototype
- **Photon**
    - 4-channel optical only - Qualified

5. HydraStar

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 onerous qualification test program, the HydraStar now has an impressive accumulation of field data with over 1.5 million accumulated operating hours over the last 4 years.

The basic parameters of the connector are listed in Table 3.

Parameter	Limits
Operating depth	23,000 feet (7,000m)
Maximum optical attenuation (per random mated pair)	Better than -0.5 dB (no matching of pairs required)
Maximum continuous voltage	1000 Volts AC_{rms}
Maximum continuous current	10 Amps

Table 3 – HydraStar Connector Specification

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. Figure 1 shows several HydraStars and parking positions installed on an optical junction box.

Figure 1 –HydraStar Optical Connectors & Optical Junction Box

5.2 Testing & Track Record

The connector underwent significant and rigorous testing with emphasis on the three original criteria regarding the challenges of fiber-optic wet-mate connectors i.e. the alignment and coupling of these very fine 9µm diameter glass fibers: (1) underwater without any contamination across the optical faces, (2) underwater without high optical losses and (3) to operate underwater for long periods of time without discernable degradation.

The first two were easily confirmed by extensive testing and backed up by subsequent experience in the field while the third relates to success and track record in the field.

(a) Testing. The testing included the following:

- **Optical Parameters.** There are two main performance considerations for transmission of light through an optical connector:
    - Insertion Loss (IL) is the light power lost through the connection. Insertion loss is cumulative when there are multiple connections in a system therefore it is essential to minimize this loss. The test target for insertion loss is <-0.5dB per optical connection and including all cases the average optical attenuation measured during qualification was -0.28dB with a standard deviation of 0.06dB. As a general note, continued testing and Factory Acceptance Test (FAT) results continues to verify the insertion loss to be typically <-0.3dB, however we still maintain our test target of <-0.5dB.
    - Back Reflection (BR) is the amount of light reflected back to the source from the connection interface. This reflected light could affect the laser source in the form of out-of-phase feedback and results in a higher noise level relative to signal strength. Back reflection needs to be kept to a minimum in laser powered single-mode

systems. In all cases the back reflection measured was less than the test target of –45dB.

- **Electrical Parameters.** There are also two main performance considerations for the electrical elements of the connector:
    - Insulation Resistance (IR) measures the 'quality' of insulation between each electrical contact element and any other adjacent conducting element (other contact elements or the connector body). IR needs to be as high as possible to minimize unwanted system electrical losses within the connector. The test target was >1Gigohm (10^9ohms) and in all cases the electrical IR measured exceeded this value.
    - Contact Resistance (CR) measures the resistance through each connector electrical contact. Contact resistance needs to be as low as possible and again in all cases the measured contact resistance was less than the design parameter of 0.1ohm.
- **Deep Ocean Environment Pressure Cycling.** The test chamber used chlorinated 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.
- **Sand/Silt Testing.** Extensive mating/demating 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 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.
- **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.
- **Durability.** The two initial test connector sets were successfully mated and demated hundreds of times at various pressure levels and pressure cycles. Since then, other testing required for specific applications has led to connectors being cycled similarly hundreds of times at various pressure levels and pressure cycles without discernable degradation.
- **Mating/Demating Forces.** In all cases the mating and demating forces were less than 50lbs, throughout the mating/demating sequences.
- **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 for less than or equal to the maximum specified -0.5dB optical attenuation 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 but testing of the HydraStar continues to this day, especially to meet various specific and unique customer requirements and applications.

Additional testing by other third parties to further qualify and evaluate the connector has included:

- Hyperbaric testing, pressure cycling, shock testing and vibration testing

Figure 2 shows both halves of a HydraStar set.

Figure 2 – HydraStar Electro/Optical Wet-Mateable Connector

(b) Track Record. Current reliability data 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 1.5 million hours with a calculated MTBF of better than 525,900 hours with an 80% 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 third 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).

5.3 Failures

To date we have had one reported failure of the HydraStar and although this data is included in the MTBF calculation above it did not occur whilst the connector was operating in the field. It occurred during a customer's own series of qualification and evaluation activities on the HydraStar. This was part of the Antares Collaboration (underwater optical telescope) in Italy. The failure witnessed by Antares was a sliding sleeve that momentarily stuck open. The cause of the problem was an incorrectly sized sliding seal O-ring that had been fitted on one connector half that was unfortunately not picked up. The discovery and subsequent analysis confirmed no inherent design fault and efforts have been put in place to further prevent the occurrence of the original Quality Control defect.

5.4 Application, Damage, Education

There have been other instances of problems with the operational use of wet-mate optical connectors. In each case we work with the customer in establishing the nature and solution to the problems. The findings have always been categorized into three main groups:

1. Application
2. Damage
3. Education

These three items relate to each other very strongly and are further expanded as follows:

1. Application
   - Suitability
   - Location
   - Installation
   - Operation
   - Packaging & Shipping
2. Damage
   - Mechanical
   - Chemical
   - Misuse
   - Accident
   - Packaging & Shipping
3. Education
   - Misuse
   - Incorrect operation
   - Pre-deployment checking
   - Maintenance and equipment
   - Packaging & Shipping

The basic problem though is education, education about optics, wet-mate optical connectors, how to specify, how to apply, how to use, how to install, fiber-management including how to handle fibers. Whilst many operators would rather fit and forget, it is not always possible for a fluid-filled pressure compensated connector offering a new technology, without attention to some basic details that require some basic education and training. In all cases we now offer standard recommendations when dealing with optical wet-mate connectors:

1. Education
   - Application engineering
   - Training courses
   - Introduction to the basics of fiber optics
   - Operation and Maintenance manual
2. Application
   - Application engineering
   - Advice on location, installation and operation
   - Specification
   - Recommendations for modification to suit application
3. Damage
   - Recommended spare parts list
   - Storage of standard spares
   - Storage of key replacement items
   - Fast repair turn-around

Whilst the industry is starting to take notice of these recommendations it is still surprising how few end-users take notice.

5.5 Failure Mode, Effects & Criticality Analysis (FMECA)

Some end-users go to the other extreme, which is very encouraging. One client performed an independent FMECA on the connector and made subsequent recommendations for the product. In this case every single piece-part was analyzed including an assessment of the effect of each identified failure mode combined with an assignment of consequence and probability to produce a Criticality Matrix.

As a result of this there were a number of recommendations for the HydraStar:

- Additional electrical barriers – Implemented as a retrofit to enhance the insulation of the contacts
- Enclosure of the receptacle spring – Implemented in subsequent derivations
- The addition of a cover over the plug – Implemented in subsequent derivations, for two reasons; one was as an anti-tamper cover, to physically prevent personnel pulling back the cover sleeve, something we had noted occur in the field and the second as a protection against dropped objects or other hazards such as being knocked by an ROV/AUV or used as levers or foot-rests by divers.

5.6 Industry Trends

At the same time we observed a trend for keeping optics and electrics separate rather than a hybrid product. This was something we endorsed particularly as the addition of the electrics into the HydraStar was the single design element that had the most impact on connector size.

Over the same time period we noticed a trend within the UK and USA Defense sectors for a move away from the use of silicone oil as a pressure compensation fluid. Subsequently we assessed the impact in using on electro/optical products. We concluded there were positive reasons to change from using silicone to an alternative pressure compensation fluid.

5.7 Lessons Learned

As with all new products, the aim of extensive qualification testing is to prove fitness for purpose and eliminate any design flaws. These ideals were demonstrated during the qualification test program however direct customer feedback and industry trends also yielded the following lessons learned identified in Table 4. This list includes all original feedback from customers from the prototype design stage until the present day. (Note that all of these lessons were addressed in the following subsequent derivatives of the HydraStar; the HydraLight and MicroStar);

Lessons Learned	Progress Made
Lack of track record	Track record increasing steadily with an impressive MTBF
Small population sample	Sample population still small but quantities in field increasing steadily
High Cost of Connector	Large development costs need to be offset but cost will reduce as quantities increase and standardization improves
Large Size of Connector	HydraStar is the size it is to meet the challenges laid down for wet-mate connector design. Electrics had the most significant impact on connector size. HydraLight and MicroStar connectors are smaller (but have no electrics).

Table 4 – Lessons Learned and Progress Made (continued)

Lessons Learned	Progress Made
Additional electrical barriers on contacts	Implemented retrofit to include additional secondary electrical barriers within connector.
Change of elastomer material	Change away to more compatible elastomers to suit oil & gas environment
Change of pressure compensation fluid	Change away from silicone for enhanced performance
Addition of stronger main springs	Stronger springs added
Addition of cover over plug sliding sleeve	Implemented on HydraLight and MicroStar
Enclosure of receptacle spring	Implemented in HydraLight & MicroStar configurations
Portable field service kits and test connectors	Recommend specific customer owned systems to suit customer configurations
Training	Recommended training programs
Spares	Recommend consideration for spares to suit usage

Table 4 (continued) – Lessons Learned and Progress Made

6. HydraLight

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 downsized optical only HydraStar that incorporated the following additions:

- Smaller size
- Optical only (up to 8 channels)
- Addition of plug cover sleeve
- Enhanced change of compensation oil and elastomers
- Stronger springs and enclosure of main springs
- Seawater compatible interior

SEACON currently have two versions of the HydraLight:

1. Military stab-plate version
2. Oil & Gas ROV version

Figure 3 – HydraStar (upper pair) and HydraLight Military Version (lower pair) Optical Wet-Mateable Connectors

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 Oil & Gas ROV version being the direct optical-only HydraStar replacement for long-term applications as expected within the underwater oil and gas industry. Figure 3 shows the size comparison between a standard HydraStar set and the military stab-plate version.

6.2 Technical Changes

Removal of the electrics led to an immediate size reduction and the addition of a cover sleeve around the plug was easily incorporated. Enclosure of the receptacle spring was more of a challenge but was achieved efficiently in the ROV version.

The change of compensation oil proved to be more of a challenge. The reason for initiating the change is that there appears to be a trend within the Defense industries away from the use of silicone as a compensation fluid. The primary reason they have for this concerns collateral silicone contamination on other molding processes within the factory or particularly during field installations. We have not seen evidence of such contamination as successful procedures have been generated to deal with the use and containment of silicone within the factory. However the selection of alternatives was carried out and a synthetic oil was selected as a possible replacement and with due consideration we re-qualified the connector to confirm the new fluid's performance.

The final findings in assessing the advantages of the potential change were positive and it was decided to change and re-qualify the connector with synthetic compensation oil. The advantages are:

- Improved lubrication
- Improved dielectric strength with a 50% higher dielectric withstand voltage
- Improved water absorption properties

Another very positive knock-on effect in using alternatives to silicone oil was the ability to select an alternative elastomer for use within the HydraLight and HydraStar. A particular compound of fluorosilicone was selected and has proved to be a robust alternative with a greater degree of compatibility with the types of chemicals used in the oil & gas industry.

These have been very positive changes, now successfully concluded by two independent re-qualification test exercises on both the HydraStar and military stab-plate HydraLight, one by SEACON and the other by a third party. The extensive re-qualification included compatibility testing, pressure testing, temperature and sand/silt testing and durability, which all successfully confirmed the design changes and now these qualified HydraStar and Military HydraLight products are operating successfully in the field.

An additional change was also incorporated on the ROV version for 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. Whilst this change was incorporated it necessitated the use of significantly more expensive internal piece parts and thus had an impact on price.

6.3 Testing

The qualification testing of the HydraLight has been extensive and onerous. Covered by two separate test programs, one for the stab-plate version for military use and the other for use within the oil and gas industry:

(a) Military Stab-Plate Version. The testing was conducted by third party personnel at Southwest Research Laboratories in San Antonio, Texas and included:

- Optical testing
- Over 440 mate/demate cycles in total
- Mate/demate cycles in clean seawater
- Mate/demate cycles in clean seawater to 9,800 feet (2,987m)
- Mate/demate cycles in sandy/silty seawater (to a pre-determined mix)
- Mechanical testing as part of host system

In all cases the testing showed good connector optical and mechanical performance within specifications throughout. Figure 4 shows the front ends of the military stab-plate version.

Figure 4 – HydraLight - Stab-Plate Version

(b) Oil & Gas Version. The testing was conducted by SEACON personnel at Southwest Research Laboratories in San Antonio, Texas and included:

- Optical testing - Insertion loss and back reflection
- Mechanical - Helium leak testing, misalignment, locking device and mating forces
- Hyperbaric to 10,000psi (23,000 feet, 7,000m) - Pressure cycling and mate/de-mate under pressure
- Turbid tank - Wet mating test, partial mating test, testing horizontal, vertical and at 45°
- Environmental stress tests - Thermal shock, mechanical shock and vibration

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 (FMS).

These were completed by Bennex Omnitec in Norway and included:

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

Jumper assembly

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

Figure 5 – HydraLight - ROV Version, Flying Lead Half

6.4 Track Record

The HydraLight is now operating in the field and available in both the stab-plate and ROV version. Over two-dozen have now been supplied but the sample population is still too small and too recent to calculate significant accumulated operating hours and MTBF.

Figure 5 shows the flying lead half of the ROV version, which was specifically developed and qualified for the oil and gas industry. It was qualified to meet the very onerous Norsk Hydro, Statoil and Elf Exploration connector Specifications that cover the specification and testing of optical wet-mateable connectors.

7. MicroStar

7.1 Introduction

The second such derivative of the HydraStar was the smaller MicroStar. 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
  - Design challenges
  - New internal materials and techniques
- Higher temperature rating (121°C)
  - Elastomers
  - Compensation
  - Expansion
- Chemical compatibility
  - Elastomers
  - Contamination fluids
- Subsea-tree/tubing-hangar interfaces including:
  - Space constraints
  - Stack-up tolerances
  - Keying, installation, securing, compliance, sealing
  - Mate/de-mate, lifecycle, water-venting

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.

7.2 Testing

Prototype testing and qualification testing is in progress. Initial testing will confirm the basic principles of the design and will be 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 to simulate actual operating conditions and verify that the connector remains within specification. These tests will be more onerous in the form of:

- Hyperbaric testing - Pressure cycling and mate/de-mate under pressure
- Turbid tank - Wet mating test
- Tree Interfacing – Installation and mate/De-mate
- Environmental stress tests - Temperature testing, thermal shock, mechanical shock and vibration

8. Photon

8.1 Introduction

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

The Photon connector is a different concept connector altogether, compared to the HydraStar. It draws on over 34 years of experience in underwater mateable connector design and over 9 years specifically in underwater optical connector design.

Several prototype initiatives proved the basis of the concept under hyperbaric and agitated sand/silt test conditions, leading to a continuation of the development.

It is a 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
- Optical insertion loss of less than 1dB
- Mate/demate cycles of less than 50

8.2 Testing

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

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

After successful conclusion of the basic testing the connector will be issued to an independent third party to perform additional testing, including a statistical analysis of the insertion loss over about a dozen connector sets. Figure 6 shows a prototype Photon connector set.

Figure 6 – 4-Channel Photon Optical Wet-mateable Connector

In addition to this the following MIL tests will be conducted:

- Vibration to MIL-STD-810E
- Shock to MIL-STD-810E
- Saltwater immersion to MIL-HDBK-729
- Salt fog external exposure to MIL-STD-810F

8.3 Track Record

The first batch has been delivered to the customer who is conducting an independent evaluation on them. Results are looking very promising with stable optical readings under typical operating conditions.

9. Summary of wet-mate optical connectors and applications

Table 5 summarizes the connectors in terms of testing and track record:

Connector	Testing	Track Record
HydraStar 8-channel electro-optical (hybrid)	• Qualified to 23,000 feet (7,000m) • Sand/Silt • Mechanical	• Field proven • 9,900 feet (3,017m) • 1.5 million accumulated operating hours • MTBF of better than 525,000 hours
HydraLight 8-channel optical, stab-plate version	• Qualified to 9,800 feet (2,987m) • Sand/Silt • Mechanical	• Field proven • Classified military project

Table 5 – Optical Wet-Mate Type, Testing & Track Record Comparison (continued)

Connector	Testing	Track Record
HydraLight 8-channel optical, ROV version	• Qualified to 23,000 feet (7,000m) • Sand/Silt • Mechanical • Compliance – Norsk Hydro, Statoil and El Exploration	• Connectors delivered to several customers but not operating in field yet
MicroStar 4-channel optical	• Qualification in progress to 23,000 feet (7,000m)	• None
Photon 4-channel optical	• Qualified to 3,200 feet (1,000m) • Sand/Silt • Mechanical	• Connectors delivered to customers but not operating in field yet

Table 5 (continued) – Optical Wet-Mate Type, Testing & Track Record Comparison

Table 6 summarizes the connectors in terms of relative cost and performance:

Optical Connector	Relative Cost	Relative Optical Performance	Relative Lifecycle (Mate Cycles)
HydraStar	High	High	High
HydraLight	Medium	High	High
MicroStar	Medium	High	Medium
Photon	Low	Medium	Medium

Table 6 – Optical Wet-Mate Relative Cost, Optical Performance and Lifecycle Comparison

10. Standardization

The issue of product standardization has deliberately not been addressed in this paper apart from a brief mention as to it being a key aim in product design and development. In almost 100% of enquiries, standardization does not even become a main driver based on the following main parameters involved in competitive bidding;

- Is it qualified?
- Does it have a track record?
- What is you best delivery?
- What is your best price?
- Built for purpose?

11. 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 products, the Photon. Also highlighted are the key elements identifying the relativity of these to: qualification testing, track record, cost, performance and lifecycle.

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 of qualified components available for use within the offshore and subsea oil and gas environs including deepwater.

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