Operational Considerations for Underwater-Mateable Connectors

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***Abstract* – Underwater-mateable connectors have enabled underwater industries to build modular components for subsea use. In particular, these wet-mate technologies have allowed subsea systems to be assembled on the seafloor. This has allowed the user to maximize modular system size and weight within the constraints of their installation equipment whilst, once installed subsea, still able to connect these modules to use interconnected and distributed communication, control and monitoring systems. A major consideration in the selection of underwater-mateable connectors is the intended mode of operation of that product with reference to it's specification and hence cost. The purpose of this paper is to highlight these operational considerations in ensuring a selected connector component will suit the intended service, for the required lifetime, at the correct cost.**

I. INTRODUCTION

Underwater-mateable connectors are used for joining up electrical or optical circuits underwater. They provide a termination of an underwater cable or oil-filled hose, containing electrical conductors or optical fibers or both. This allows divers, Remotely Operated Vehicles (ROV's), Autonomous Underwater Vehicles (AUV's) or automatic connection systems, to facilitate the connection of the two halves underwater. The impact of being able to do this has enabled significant progress in the modularization of underwater systems in the oil and gas, defense and oceanographic industries, allowing the following:

- Modular sub-systems to be installed underwater, one at a time, and then later interconnected together to distribute power and communications, forming larger underwater systems.
- Facilities to include ports for diagnostic maintenance activities or for future expansion.
- Modular systems designed to suit the constraints of the installation equipment being used.

The remoteness and depths of installation combined with the high cost of marine operations requires underwater mateable connectors to be very reliable in order to be cost-effective. Diagnostic and repair of such components at remote locations can be very expensive. In this respect careful consideration must be made to ensure a proper match between application requirements and the capabilities of that connector during operation. For this reason connectors, as components in underwater systems, should properly be considered as critical supply items. Factors beyond the obvious; cost, availability and size, are; suitability, ease of use, reliability, and the consequence of connector failure. Whilst all of these points need to be fully considered, it is the intent of this paper to focus on the operational considerations in the selection of the right connector, for the right application and at the right cost.

II. DIVERSITY OF UNDERWATER-MATEABLE CONNECTORS

Underwater-mateable connectors, also known as "wet-mate connectors", have been around since the 1960's. In that time they have ranged from the most inexpensive rubber molded electrical wet-mates to the state-of-the-art optical wet-mate products. This has resulted in a huge range in the type of products available and a large number of suppliers providing choice. We can categorize the current diversity into generic groups of underwater-mateable products. All of these products (listed in approximate order of increasing unit cost) have been extensively qualified and tested and are in operational use:

A. Miniature Rubber Molded Electrical Wet-Mate Connectors

These are molded, typically in Neoprene or Hypalon, in a number of different configurations such as the MICRO WET CON™ or the ALL WET™ flat series. They can be capable of high pressures and are typically rated up to 300 Volts. They are small in size and low in cost. These products can be inexpensively molded onto jacketed cables and are easy to use in the field. The materials of construction limit temperature ratings.

B. Rubber Molded Electrical Wet-Mate Connectors

Similarly molded, typically of Neoprene or Hypalon, in a number of different configurations such as the WET CON™ or the ALL WET™ connectors. They can be capable of high pressures and are typically rated up to 600 Volts. They are small in size and low in cost. The products can also be inexpensively molded onto jacketed cables and are easy to use in the field. The materials of construction limit temperature ratings.

C. Metal Shell Electrical Wet-Mate Connectors

By molding a rubber connector into a metal body, greater strength and stability are added to the product along with positive and stronger keying and locking. The connector, such as the U-Mate, is now more robust and able to withstand more abusive environments. They can be capable of high pressures and are typically rated to 600 Volts. They are small in size and low in cost.

D. Pressure Balanced Electrical Co-Axial Wet-Mate Connectors

This style of connector is typically an oil-filled and pressure balanced metal shell assembly incorporating redundant sealing barriers to the environment. The term coaxial derives from the fact that the electrical contacts are coaxial metal bands, sharing a common axis. A principal advantage of this is that these connectors do not need to be keyed. As an example the CM100 series of connectors are available in 2-pin 50Ω or 75Ω impedance-matched versions or multi-pin non-impedance-matched versions. Both types are rated up to 600 Volts. These are generally physically larger and more expensive than the standard metal shell electrical connectors, but by design and experience they are inherently more robust.

E. Pressure Balanced Electrical Wet-Mate Connectors

This style of connector is also typically an oil-filled and pressure balanced metal shell assembly incorporating redundant sealing barriers to the environment. As an example, the CM2000 series of connectors have full redundant (dual) seals at all water ingress points. They are available as multi-pin connectors in various contact sizes of voltages up to 3,300 Volts AC and currents of 10 Amps, 30 Amps, 60 Amps and 100 Amps. These are also physically larger and more expensive than the standard metal shell electrical wet-mate connectors, but by design and experience they are also inherently more robust. These are the electrical connectors most suitable for extremely deepwater, remote and critical, long-term applications.

F. Pressure Balanced Optical Wet-Mate Connectors

These connectors are typically a metal shell assembly incorporating single sealing barriers to the environment. Examples are the Photon and S-Series connectors, that offer a relatively low cost and small size optical underwater-mateable connector. The optical coupling takes place in an oil-filled area and the connector can maintain optical insertion loss of better than –1dB and optical back-reflection of better than –25dB.

G. Pressure Balanced Optical Wet-Mate Connectors – Joined-Chamber

This style of connector is also an oil-filled and pressure balanced metal shell assembly but incorporating full redundant sealing barriers to the environment. Examples are the HydraStar, HydraLight and MicroStar series of connectors. All utilize a “joined-chamber” coupling technique where the optical ferrules from each separate connector half are coupled within a common, benign, pressure compensated, oil-filled, “joined-chamber”. They can maintain optical insertion loss to significantly better than –0.5dB and optical back-reflection of better than –40dB. These are the optical connectors most suitable for deepwater, remote and critical, long-term applications.

III. CONNECTOR COMPONENTS

An underwater mateable connector is typically composed of two main systems:

- Front Wet-End System – This is the ‘active’ part in each connector half. Some form of sealing technology allows the active electrical or optical coupling elements to take place in an underwater environment. One half is usually a ‘male half’ and contains pin contacts and the other half is usually the ‘female half’ and contains socket contacts.
- Back-end and cable termination system – This accomplishes the termination and sealing of the cable and connects the electrical or optical circuits into the back of the connector.

These two systems can contain quantities of components ranging from a very few in the case of the simple rubber-molded connectors to a multitude of components in the optical or ultra-high reliability connectors. Generally the varying degrees of complexity of these halves have a directly proportional impact on cost. The increased complexity is usually associated with the type of cable termination required combined with the anticipated lifetime required for the connector. This relates directly to the estimation of operational conditions a connector is likely to experience in an application.

If we examine each connector by breaking it down into these core components, each of these components can be individually assessed for failure modes. These failure modes can further be explored by analyzing the cause of each failure along with the probability of each failure and the effect of the failure on the host system. By analyzing this information, the key elements of probability of failure and criticality of failure can be built up into a criticality matrix to identify any potential weak points in the connector design that have a direct impact on system design. This is called a Failure Mode Effects and Criticality Analysis (FMECA). Whilst the FMECA is not discussed any further in detail here, it is mentioned at this stage to introduce examples of generic failure modes and their causes.

IV. GENERIC FAILURE MODES AND CAUSES

At the top level there is one main failure mode of a connector and that is if it fails to facilitate the transfer of the appropriate amount of electrical power or light power required. The cause of a connector’s inability to perform this function can be traced by examining the root cause of individual component failures. It is possible to categorize these into the situations where the operational use of these connectors has an impact on system failure. In examining these components it is possible to group into the following generic failure types and subsequently highlighting the operational contribution for each:

- Corrosion
- De-lamination
- Elastomer degradation
- Damage
- Premature unlatching
- Seal failure
- Inadequate long-term protection

A. Corrosion

Connector corrosion is mainly due to incorrect metal selection or incorrect installation of the connector for a particular application. It is recommended that the seawater-wetted metal required, for the connector, should be specified by the purchaser during the specification and procurement cycle. Operational problems that can cause corrosion are; use of the connector in excessive operating temperatures beyond their design range; incorrect connection or non-connection (dependent on host system corrosion protection philosophy) into the host corrosion protection system or; an incorrectly designed cathodic protection system.

B. De-lamination

In a connector that utilizes an elastomer bonded to a metal, a primer is used to bond to the metal and the elastomer is then bonded to the primer. Cathodic de-lamination occurs when an electrochemical cell is formed between the connector body and a cathodic protection system such as a zinc anode or induced current. The chemistry of the cell creates a highly basic solution at the bond line that eats away the primer and adhesive. This can lead to bond failure. There are three main solutions to this problem; (a) Eliminating the conductive nature of the shell; (b) incorporating a design change such that the de-lamination does not matter to the design of the connector and; (c) ensuring the connector is not used within proximity of a cathodic protection system, in which case the design requires a suitable metal selection that allows the connector to be used in total isolation in seawater.

Operationally the connector must be used within the constraints of a correct application to avoid this type of failure.

C. *Elastomer degradation*

Operational problems that can cause elastomer degradation are long-term exposure to excessive operational temperatures and/or chemical contamination. Both of these can cause rapid deterioration of the elastomer. Use of connectors within environments that are subject to these two risks need to carefully consider elastomer selection and qualification.

D. Damage

Connector damage is the main source of operational problems with a multitude of causes as follows:

- Incorrect use of the connector causing physical damage to the body or contacts. These can occur as follows:
  - Hit by third party such as ROV, diver, tool, dropped-object.
  - Not fitted with long-term protective caps (if required).
  - Physically damaged during packaging, transport, shipping, integration testing, installation, commissioning and operation.
- Excessive use of the connector beyond it’s recommended mate/de-mate life-cycle without maintenance
- Excessive force on a connector body during installation or use
- Exposure to excessive temperatures beyond it’s design range
- Exposure to excessive pressures beyond it’s design range
- Improper installation and maintenance
- Improper selection for application

E. Premature unlatching

Physical isolation of the electrical or optical circuits occurs when the connectors prematurely unlatch. This can be caused by incorrect installation of the connector in the first instance or by excessive snagging force on an attached hose or cable during operational work underwater. There is a potential secondary failure when an electrical connector is powered up during a premature unlatching. The seawater path across exposed contacts of different electrical potential can cause localized short circuits and arcing that can permanently damage the connector.

F. Seal Failure

Seal failure can be caused by a number of the above factors including physical damage, chemical damage and corrosion. Seal failure can cause water ingress leading to connector degradation. Another factor that can contribute to seal failure is connector operation in extremes of temperature. This can be either extremely cold temperatures beyond the design and qualification range of the connector not allowing the seals to fully function or extremely high temperatures that can cause premature degradation of elastomeric seals in use.

G. Inadequate Long-Term Protection

Unmated connector halves may not be designed for long-term operation or are subject to increased risk of failure in the event that they are not protected. In general, a connector half should be fully protected at all times, except for the operational-window associated with it’s underwater operations. Full protection means that exposed pin and socket contacts or optical ferrules of a single connector half are protected within the confines of the connector seals.

This is usually by a long-term protective cap, dummy connector or long-term parking place.

V. OPERATIONAL PROBLEMS

The main reason why operational problems are critical is cost. Any critical component failure may have a direct impact on the offshore activity in progress whether it is research, exploration, drilling or oil and gas production. The impact is dependant on the design contingency and redundancy system incorporated. Ultimately in an ill-thought-out design, key component failure can lead to program delays and additional offshore resources being required. The cost of these, are significantly increased by the usual remote location and operating water depth of these projects.

It is critical that operational problems are minimized so that project uptime is maximized. Most major projects put a considerable amount of effort into assessment of system availability and reliability. These are usually models that utilize actual reliability data when available or theoretical data when not, but they are only predictive models. At the end of the day, the suitability of the product for it's intended application is what counts.

VI. CAPEX VERSUS OPEX

Another critical parameter in the design and specification of subsea systems is the traditional trade-off between 'capital expenditure' also known as CAPEX and 'operating expenditure' also know as OPEX. To further explain these, CAPEX is the capital expenditure incurred in the development of a project and is the cost to purchase, install and test a system before it is operational. OPEX is the operating expenditure incurred to keep the system operational over the lifetime of the project. Due to the remoteness and location of offshore projects, both the capital expenditure and operational costs tend to be very high. The Project Team is under pressure to keep capital costs down and may select the least expensive solution. The Operational Team is under pressure to keep operating costs down and want an extremely reliable, but perhaps more costly initial solution. It is important to strike a balance.

The CAPEX cost of a critical connector may be insignificant when compared to the consequences of that connector causing offshore downtime. This can be mitigated, by minimizing the significance of the connector on system performance, say by redundant design. However the most appropriate criteria for connector selection is it's suitability for the task. The suitability for the task is defined by two main parameters: design and testing. Firstly, the connector is designed to meet a set of specifications and secondly that it is tested to meet those specifications, including extremes.

A. Low CAPEX / High OPEX Solution

Using a connector as an example to highlight the CAPEX / OPEX trade-off, we look at a LOW CAPEX – HIGH OPEX solution. A $25 rubber molded connector that is suitable for shallow water operation behind a protective cover in a swimming pool. This would be adequate and safe for long-term use in the relatively benign operational environment if;

- It is not exposed to the risk of damage by swimmers because it is installed behind a protective cover
- The underwater pressures are not great therefore the pressure/test margin is large
- It is not mated and de-mated continuously under water
- It does not operate in a highly corrosive saltwater environment
- It is not subject to the presence of highly contaminating fluids

However this type of connector would not really be suitable for use on a deepwater work-over control system operated from the deck of a ship under the following conditions:

- Extremely hot equatorial temperatures
- Pressure cycled to 5,000psi once or twice a week
- Operated by inexperienced handlers
- Not maintained properly
- Contaminated by unsuitable operational fluids
- Mated and de-mated several times a week underwater

It is not expected that this $25 connector would last long in such an application. There would be significant operational costs in replacing the connector, re-installing onto a cable and re-testing every time it failed, which we could assume would be a minimum of once per year. So every year there would be operating costs of about $10,000 per repair if you take into account the costs to fly repair personnel out to sea, provide food and accommodation and purchase replacement parts. This solution is known as a LOW CAPEX / HIGH OPEX solution.

B. High CAPEX / Low OPEX Solution

The high CAPEX, low OPEX solution is derived from understanding the operational environment a connector is intended to work under. It takes into account all of the operational parameters and considerations, ensures they are adequately addressed in the design and qualification testing of the connectors. Detailed design and qualification testing is expensive, particularly for a product engineered to suit deepwater marine environments that are subject to intense pressure cycling, temperature cycling (i.e. deck of a ship at equatorial temperatures installed to colder deepwater temperatures), fluid/chemical contamination and general rough handling by inexperienced personnel topside and ROV's underwater.

In this case a connector may cost $10,000 but has a significantly increased probability of performing many years in operation, even under these arduous conditions. It will still be subject to random failures or operational damage but these are likely to be far less. Say once every five years a random failure occurs or the connector is damaged. So every five years there would be operating costs of about $20,000 per repair if you take into account the costs to fly repair personnel out to sea, provide food and accommodation and purchase the more expensive replacement connector parts. This solution is known as a HIGH CAPEX / LOW OPEX solution.

To demonstrate this point, we offer the following comparison table (for simplification, we have excluded effects and costs associated with consequent loss of production, delays to project, effects of inflation, varying costs of repair and Net Present Value calculations).

Table 1
SIMPLIFIED CAPEX / OPEX COMPARISONS

Solution	Initial CAPEX	10 Year OPEX	Total Costs
Low CAPEX / High OPEX	$25	$100,000	$100,025
High CAPEX / Low OPEX	$10,000	$40,000	$50,000

VII. OPERATIONAL CONSIDERATIONS

We have explored the main failure types and principle operational causes. These being: corrosion, de-lamination, elastomer degradation, damage, premature unlatching, seal failure and inadequate long-term protection, along with a comparison of differing CAPEX versus OPEX options. What do we have to do to mitigate these concerns and minimize operational problems?

Figure 1
OPERATIONAL CONSIDERATIONS' CIRCLE

Consideration should be given to all elements of a connector's life as shown within the "Operational Considerations' Circle" in figure 1. These are all elements of mitigation working towards ensuring a selected connector component will suit the intended service for the required lifetime, at the correct cost.

A. *Communication*

The most important aspect of how the required connectors are specified is communication. This is a two-way process between supplier and purchaser. The User/Purchaser must know exactly what they want, the Supplier must know exactly what is wanted and both parties must clarify exactly what is unknown. If a User does not know exactly what they want then the correct Supplier will have enough experience to assist and help define the requirements.

One way of 'communicating' the exact requirements is through the issue of a Specification. The Specification is a way of ensuring both the User and Supplier do their homework. The purchaser tries to spell out exactly what is required and the supplier ensures they are fully compliant or at least should highlight any non-compliances. It is in this document that any particular or peculiar "operational considerations" should be clearly identified, details such as: pressure (operational and test), temperature (operational and storage), lifetime, compatibility with fluids etc.

B. *Design*

The Specification document fully defines the intended applications and operations. The resultant product will either be; an existing design, an existing design that is modified to meet the requirements or a new design. Careful application engineering by the supplier and agreement by the user is required in ensuring suitability of the design.

C. *Manufacture*

The manufacture and testing of the connector should be in accordance with industry standards for Quality and Inspection systems.

D. *Qualification*

To complement the actual design an awareness must also be made of the testing that has been successfully completed or needs to be performed on the connector to ensure the design meets the specification.

E. *Packaging*

Another critical part of the connector supply is the correct packaging of the products in preparation for transit to their required destination. This must address all packaging specification requirements of the purchaser, such as preparation for shock, vibration and shipping temperatures etc. and also any specific guidelines or limitations that the supplier needs to highlight, such as protection of optical fiber or electrical wire pigtails etc.

F. *Shipping*

Once correctly packaged, the next most important aspect is the actual shipping conditions for the products to the required destination. Again this must address all specification requirements of the purchaser, such as shock, vibration and temperatures etc. and any specific guidelines or limitations that the supplier needs to highlight to avoid damage during shipping.

G. Installation

The next consideration is installation of the connectors into their host system and additional protection requirements that may be required before final use underwater. Examples of this are the use of long-term or short-term protective caps on unmated connector halves before the final hook-up and connection of the systems underwater. 'Installation Guidelines' should be provided by the supplier.

H Operation

A connector must be operated within it's intended parameters including it's depth rating and temperature rating in addition to the compatibility to operational fluids and contaminants with the connector body materials. An important point of connector operation extends to land testing that will probably be carried out in advance of the connectors going subsea. This may include consideration of additional temperature such as arctic or equatorial operating temperatures. It also may include pre-deployment operation on the back of a vessel and post-deployment testing as part of the host system underwater commissioning.

I. Maintenance

Maintenance of a connector system is also a prime consideration with particular care taken to educate the users of the connectors about operating parameters. This includes particular service requirements (if any) and support in the event of connector damage or failure. For example, when a connector with a rating of 100 mate/de-mate cycles has been cycled approaching that number, planned maintenance is recommended at the next available opportunity, should it be economic to do so. Service and support is usually requested by the User at the last possible opportunity and as such it is recommended that connectors in critical operations are included in a maintenance program including training, spare parts stocking and availability of trained personnel.

J. Education

Education is probably the most important aspect of operational considerations of underwater mateable connectors. This is a two-way communication path in that the User must 'educate' the Specifier and ultimately the Purchaser of the application and requirements and the Supplier must 'educate' the purchaser and user about the connector.

VIII. CONCLUSION

In all cases the operational considerations of underwater mateable connectors are a critical aspect of their specification, procurement and use. These operational considerations have been highlighted to raise awareness in ensuring a selected connector component will suit the intended service for the required lifetime and at the correct cost.

Acknowledgments

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