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The Development of a Cable Termination System for Deep Water Applications

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Abstract

As offshore developments are pushed into deeper waters, new enabling technologies are required to terminate electrical, optical and hybrid cables. Recent experience has shown that, depending upon cable construction, two failure modes are possible.

Firstly, in many cable terminations, the individual cores of the cables pass from an atmospheric cable breakout chamber into a dielectric fluid-filled pressure-balanced splice chamber. Even supported core elements can collapse into the atmospheric cable breakout when used in deep water applications, resulting in damage to the conductors. Secondly, many cable terminations have a single sealing element separating the oil or gel-filled volume from the cable and conductor interstices which are, in many cases, atmospheric. If this sealing element is compromised, the resulting venting of the oil can lead to failure of the termination.

A new, key enabling cable termination technology has been developed to extend the operational depth and significantly increase the reliability of cable terminations. This modularized system completely isolates the cable elements from the pressure-balanced splice chamber and ambient environment. This approach to cable termination eliminates cable-dependent design limitations and common mode/single point failures. This paper provides an overview of the current designs and typical failure modes. It then provides a description of the new termination system and the solutions it offers.

Introduction

As oil and gas production projects move into deeper waters, new key enabling technologies are required to terminate electrical, optical and hybrid subsea umbilicals. Two failure modes have been identified using current termination technology in deepwater applications: core element collapse into an atmospheric breakout region and wicking of the compensating fluid from the termination, past a single sealing element, into the interstices of the cable or conductor. Either failure may lead to partial or catastrophic failure of the termination. Each failure mode can be directly linked to the interaction of the cable elements with the pressure-balanced dielectric fluid-filled splice region in the termination.

Both of these failure modes have been encountered in the recent past during the installation phase of ultra-deepwater developments. In each instance, an understanding of the failure mode led to the development of design modifications that were qualified and successfully deployed. The difficult lessons learned from these experiences have resulted in new design considerations and more rigorous qualification procedures during the development of cable specific Field Installable Termination Assemblies (FITAs). These lessons have also been cause to rethink the design philosophy of cable terminations. Ocean Design, Inc. (ODI) has embarked on an ambitious design program to eliminate the limitations of the current technology and increase the reliability of their terminations. The result of this effort is the FACT (Field Assembled Cable Termination) system; a modularized termination system that completely isolates the cable's internal elements from all pressurized fluid interfaces. This paper will detail the common failure modes of the current technology along with the mitigating remedies and preview a new technology for terminating cables for deepwater applications that eliminates known failure modes.

Conductor Core Collapse

Core collapse may be divided into two subcategories: push-back and bird-caging. Figure 1 details a common design used for subsea cable terminations that is susceptible to both forms of core collapse when deployed in deepwater. Starting from the right side of the figure, the cable penetrates the termination through an elastomeric outer boot seal which provides the primary barrier to water ingress. A compression cable grip is used to capture the outer cable jacket and provides mechanical strength. An elastomeric breakout boot seal is installed over the cable end to isolate the cable from the potted module in the event of flooding with seawater. As the potted module is isolated from any fluids by design, it may be essentially considered atmospheric. Each conductor is passed trough a self-activating bi-directional elastomeric gland seal and then through an elastomeric nipple boot seal into the pressure-balanced dielectric fluid-filled splice chamber. As the volumes between the gland seals and nipple boot seals are isolated from any fluid by design, these volumes may be considered atmospheric. Next the conductors from the cable are spliced to pigtails that terminate at isolated connector solder pots. Either a traditional bladder style compensator or radially compliant jumper hoses provide pressure and thermal compensation of the dielectric fluid.

Push-back is caused when a pressure gradient exists between termination modules through which a cable element is passed. The resulting load on the element, the product of the element cross-sectional area and the differential pressure between the modules, drives the cable element from the high-pressure module into the low-pressure module if the load exceeds the column strength of the element. This failure mode is typically associated with the conductor elements within the cable as they pass from the atmospheric potted module to the pressurized fluid-filled splice chamber. There is no way to predict how much conductor length will migrate from the high pressure fluid-filled splice chamber to the potted module, as this is a function of the compressibility of the potting compound and the voids which may exist within the compound. If the length of pigtail is sufficiently short, then the splice solder pots may bottom on the housing that retains the gland seals and nipple boot seals, possibly causing a short circuit or low insulation resistance condition. Additionally, the nipple boot seals and/or the splice boot seals may be compromised, possibly leading to venting of the compensating fluid from the termination.

Bird-caging occurs when the individual strands of a helically wound conductor buckle as a result of loads placed on the major element, as in the push-back case. As the individual sub elements buckle, they radially flare outward from the major element axis allowing the major element to collapse onto itself. Experiments have shown it possible for the individual strands to pierce the conductor insulation possibly leading to termination failure. This failure mode will most likely occur within the atmospheric region between the gland seals and nipple boot seals, but may occur along any loaded section of the conductor within an atmospheric module.

It is difficult to predict the behavior of the composite elements or the individual sub elements under high differential pressures. In the case of the insulated conductors, column strength of the core elements and sub elements are functions of many variables including, but not limited to: composite copper diameter, number of copper strands, copper strand diameter, insulation thickness, insulation material, and geometry. Thus far, the ratio of composite conductor diameter to the insulation thickness has shown itself to be the first order variable with regards to buckling resistance. As the ratio of the conductor diameter to insulation thickness decreases for a fixed conductor outer diameter (the insulation thickness increases), the column strength of the conductor is substantially decreased. This increase in conductor insulation thickness is required to maintain insulation resistance characteristics on long step-out and high-voltage cables. Complex analytical techniques or costly experimentation would be required to characterize this type of behavior with respect to termination design. This task would prove time consuming and costly given the number of unique cables terminated each year.

Minimizing, or removing altogether, the differential fluid pressure between modules through which a cable element passes eliminates the possibility of push-back and bird caging. In this particular design, removing the nipple boot seals in the fluid-filled splice chamber effectively eliminates the bird caging effect in that region. Using a secondary compensation system to communicate with the potted module will eliminate the push-back and bird-caging effects within that region. This has been done in current designs by retrofitting them with additional external compensation systems. The external compensator assembly allows the dielectric fluid contained within it to communicate with the potted module. As the assembly is deployed, the dielectric fluid is expelled from the compensator assembly into the potted module, thereby equalizing the pressure between the fluid-filled splice chamber, potted module and ambient subsea environment. Several experiments have proven that conductors do not collapse into the potted region, even when ambient pressures as high as 10,000 psi are applied.

Wicking

Figure 2 details a typical cable termination design that is susceptible to wicking. Starting from the right side of the figure, the cable enters the rear of the termination through an elastomeric outer boot seals that provide the primary barrier to water ingress. The armor from the cable is flared out and epoxy-potted to provide mechanical strength. The inner electrical cable jacket is passed through a self-activating bi-directional elastomeric gland seal into the pressure-balanced dielectric fluid-filled splice chamber. An elastomeric breakout boot seal is installed over the cable end to isolate it from the fluid-filled splice chamber. Next the conductors from the cable are spliced to pigtails that terminate at isolated connector solder pots. Either a traditional bladder style compensator or radially compliant jumper hoses provide pressure and thermal compensation of the dielectric fluid.

Wicking occurs when the compensating fluid vents from the termination into the interstice filled cable or conductors. This will happen when one or more sealing elements or cable elements in contact with the pressurized compensating fluid are compromised. The fluid will migrate from the high-pressure fluid-filled splice chamber into the potentially low-pressure interstices within the cable elements. This loss of fluid in itself may not lead to termination failure, but it can, under the right circumstance, initiate events that can cause partial or catastrophic failure of the termination. All commercially available termination technologies that are pressure compensated contain this “Achilles Heel” by the very nature of their design. Breakout boot seals, boot seals that interface the conductors to the termination splices or connectors and the conductors themselves within the pressurized dielectric compensating fluid, all have the potential to void the termination if compromised.

Wicking, in this case, would most likely occur as a result of a hole being developed in the breakout boot seal. In figure 2, it can be seen that the breakout boot seal has a thin wall and a small air pocket that allows the boot to distort under pressure. It is possible that the boot could be punctured by sharp edges that remain on trimmed back shield tape or filler elements within the umbilical. As the pressure increases, the boot begins to distort and comes into contact with the sharp tape and fillers. As the pressure continues to increase, the load developed at the points of contact between sharp elements and the boot exceeds the tear strength of the boot material, thereby generating a hole and allowing the dielectric fluid to vent from the termination. It is may take several hours to weeks post deployment to void the termination of enough fluid to initiate event sequences that may lead to partial or catastrophic termination failure. One such failure has occurred with this particular termination design, after the dielectric fluid was voided from the termination enough pressure was developed on the termination end caps to implode them into the termination.

The preceding scenario is not the only failure scenario that would allow dielectric fluid to vent from the termination but it is the most likely. If bi-directional gland seals o-rings, splice boot seals or conductors were compromised during installation, they would allow dielectric fluid to vent. These scenarios are less plausible as an in-build process helium leak test and submerged insulation resistance test would likely identify such flaws.

To increase the reliability of this particular design, a more robust, thick-walled breakout boot seal was designed. The boot was designed to have increased puncture resistance by increasing the thickness of the membrane above the breakout region. As four additional scenarios were postulated which may void the termination: failure of the gland seal, o-rings, conductor jacket and boot seals. A pressure relief valve was added to the design to mitigate the possible implosion of the termination end caps. To prevent the pressure relief valve from inadvertently activating, a secondary flexible external compensation system was retrofitted to the termination housing.

FACT (Field Assembled Cable Termination)

As a result of field and lab experiences, ODI has gained an in-depth understanding of the interactions of the cable elements with the design elements of traditional terminations. We believe that the solutions detailed in the previous paragraphs combined with the current design approach are adequate. We base this conclusion on the fact that several thousand of our terminations are deployed worldwide, with only a few isolated failures reported. However, the solutions themselves do not eliminate the failure modes associated with the interaction of the cable elements with the pressure balance splice chamber. It becomes apparent, after examining the failure modes, that the complete isolation of the internal cable elements from the pressurized splice chamber and ambient environment is necessary. Based on these conclusions, ODI has developed the FACT (Field Assembled Cable Termination) system; a highly reliable, modular, field assembled cable termination. The premise behind the concept is to use field proven technologies to completely isolate the cable internals from the ambient subsea environment and pressure-balanced fluid-filled splice chamber, regardless of cable construction.

The FACT assembly consists of a high-pressure penetrator assembly (see figure 3) that completely isolates the electrical, optical and hybrid cable internals from the subsea environment and pressure balanced splice chamber. The penetrator assembly consists of an outer elastomeric boot seal as a primary barrier to water ingress. This is followed by either a compression type cable grip or epoxy armor termination for mechanical strength. Depending upon the cable construction, either the outer cable jacket sheath or redundant inner cable jacket sheath is passed through a self-activating bi-directional elastomeric gland seal to further isolate the cable from the subsea environment. This field proven gland seal/boot seal combination is very robust and reliable in high and low- pressure applications. The individual conductors and optical fibers are broken out and interfaced to a “web” assembly (high pressure header) using dual redundant solder pot boot seals and/or an optical fiber lock. All interstices within the penetrator assembly are high-pressure filled with a rigid non-compressible epoxy compound to reinforce the cable, prevent the cable from pistoning inward and prevent the compressive loading of the conductors and fiber tube.

The “Web” assembly isolates the internal cable elements from the pressure-balanced, dielectric fluid-filled splice chamber using field proven Nautilus and Fiber Lock technologies. The “web” assembly has been rigorously qualified at differential pressures greater than 10,000 psi. This, and other key design features, have led ODI to file for Patent coverage for the FACT system.

The FACT penetrator assemblies may be terminated directly to atmospheric enclosures or pressure balanced dielectric fluid-filled splice canisters. It is ideally suited for a multitude of umbilical termination applications. The FACT penetrator assemblies have been designed with modularity in mind and may be used with ancillary accessories to adapt to a wide array of interfaces. Additionally, the FACT penetrator assemblies can accommodate a wide range of electrical, optical and hybrid cables, with or without gel fill. If the cables are gel filled, an ancillary pressure compensation system may be installed on the assembly allowing the internal cable pressure to equalize with the ambient environment.

Product Design and Qualification Status

At the time of submission of this paper, ODI have completed prototype design, manufacture and initial qualification testing of many of the FACT system components.

The FACT system is scheduled to complete its full qualification program at the end of June 2003. As the system is based on field proven technologies, ODI feels there is little technical risk associated with the product qualification. Qualification testing is being carried out per the applicable values specified in the technical specification section. The assembly is being rigorously qualified in three distinct phases to verify each design element and the assembly as a whole:

“Web” Qualification:
- Hyperbaric pressure and cycling
- Hyperbaric test to destruction
- High voltage

Penetrator Assembly Qualification:
- Hyperbaric pressure and cycling
- Thermal testing

Fact Termination Qualification:
- Hyperbaric pressure and cycling
- Thermal testing
- Shock and vibration

It is hoped that initial qualification test results will be provided during the presentation of this paper at OTC 2003.

Conclusion

Existing electrical, optical and hybrid cable termination designs are nearing their design limitations, as recent deepwater termination experiences have shown. Eliminating the complex interactions between the internal cable elements and pressurized fluid interfaces is of paramount importance as cable terminations are deployed in deeper waters. The FACT high-pressure penetrator provides the necessary cable isolation to ensure a highly reliable termination to support these next generation ultra-deepwater developments.

Technical Specification

Material:
- Titanium Grade 5 (isolation from cathodic protection system required)
- 316L Stainless Steel

Circuit Configuration:
- Electrical = 7 circuits per Penetrator Assembly
- Optical = TBA circuits per Penetrator Assembly
- Hybrid = 6 electrical and TBA optical circuits per penetrator assembly

Maximum Cable Diameters:
- Large Electrical Penetrator = 0.70” to 1.30”
- Small Electrical Penetrator = 0.30” to 0.70”
- Optical Penetrator = TBA
- Hybrid Penetrator = TBA

Design Life:
> 25 years

Pressure:
10,000 psi*

Voltage:
3,000 VAC/VDC*

Current:
> 30 Amps*

Insulation Resistance:
> 10 GΩ @ 1000 VDC*

Electrical Splice Resistance:
< 0.1 Ω per splice

Optical Splice Loss:
< 0.1 dB per splice

Operational Temperature:
-10 ˚C to +50 ˚C*

Shock:
6 cycles, ½ sine @ 18 ms, 30G

Vibration:
30 min, 20-80 Hz, 4G, 3axis

* Subject to cable performance

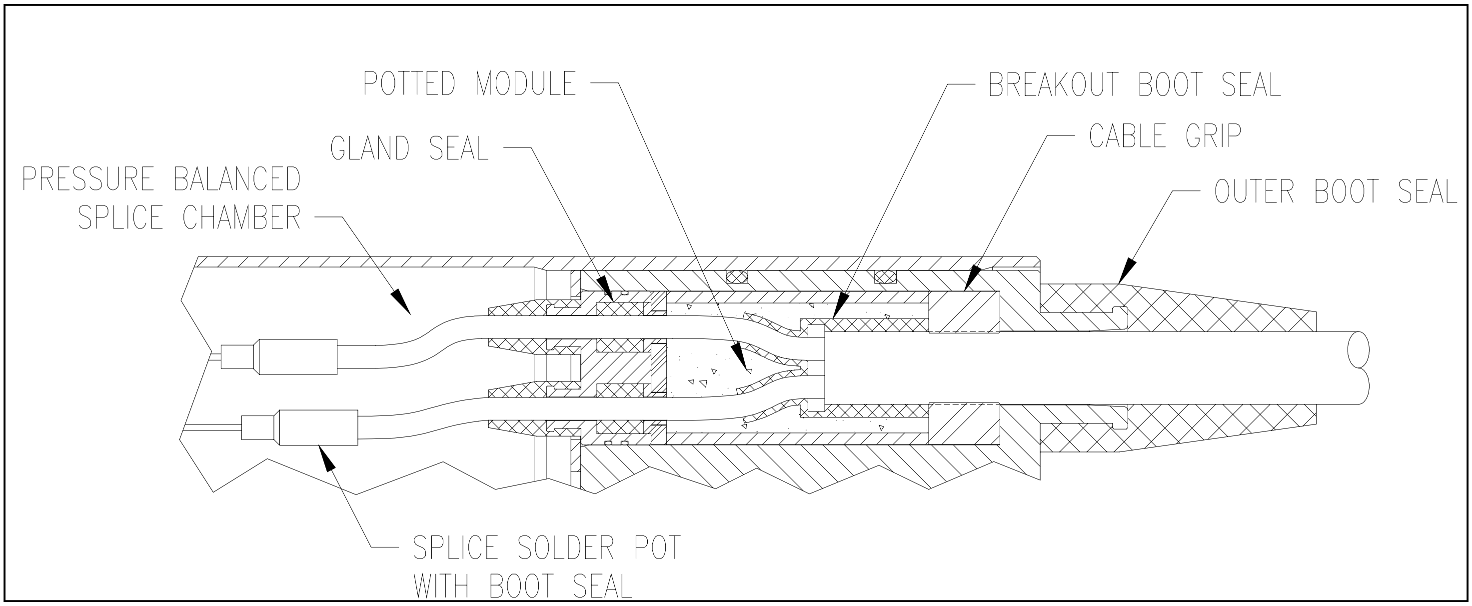

Figure 1: CONVENTIONAL TERMINATION ASSEMBLY WITH ATMOSPHERIC BREAKOUT REGION

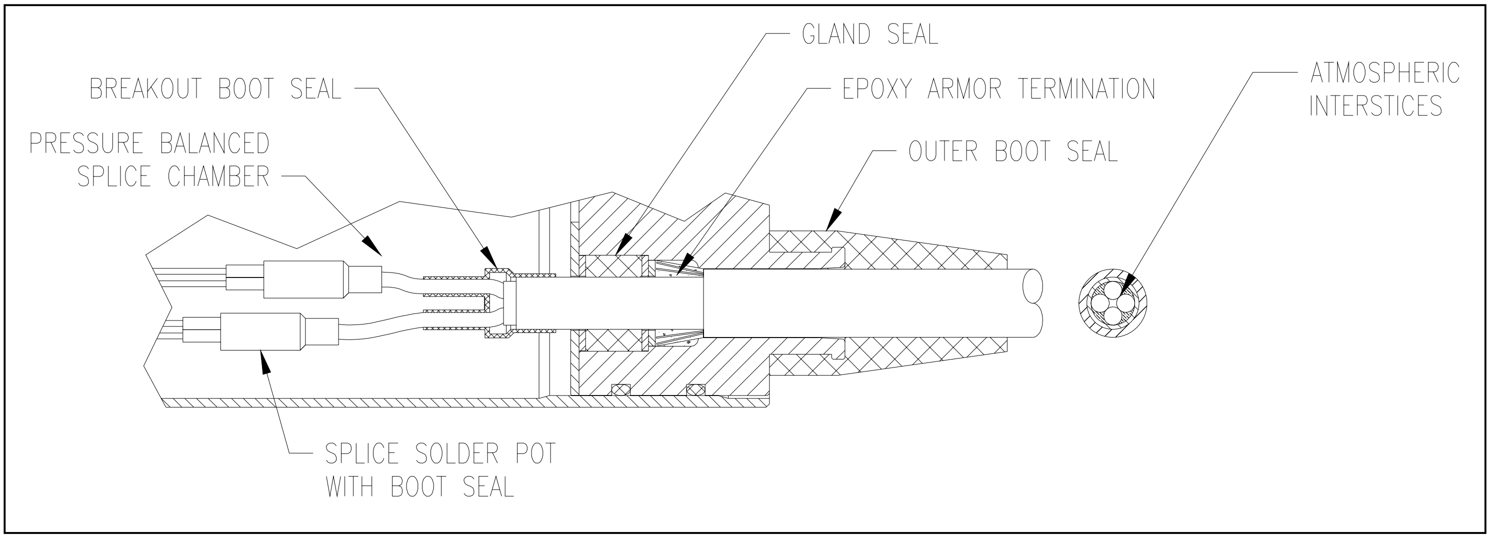

Figure 2: CONVENTION TERMINTION ASSEMBLY WITH BREAKOUT BOOT SEAL IN THE PRESSURE BALANCED REGION

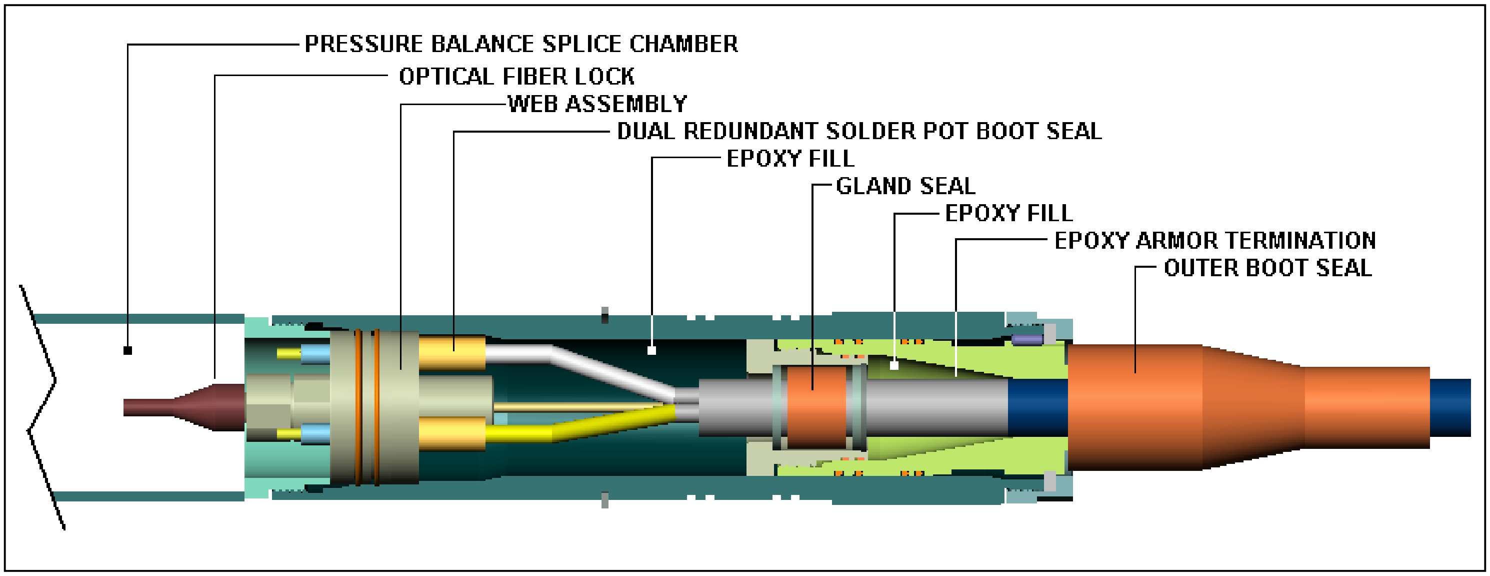

Figure 3: FIELD ASSEMBLED CABLE TERMINATION (FACT) WITH HIGH PRESSURE "WEB" THAT ISOLATES THE CABLE FROM THE PRESSURE BALANCED SPLICE CHAMBER