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MODULAR TERMINATIONS FOR ELECTRICAL AND OPTICAL CABLES WITH INCREASED RELIABILITY AND SIMPLIFIED INSTALLATION

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Abstract

A second generation enabling cable termination technology called FACT G2 (Field Assembled Cable Termination Generation 2) 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 region and the ambient environment. This approach to cable termination eliminates cable-dependent design limitations and common mode/single point failures that have previously been identified in subsea applications. This technology is suitable for both electrical and optical cables, as well as hybrid (electro-optical) cables.

This paper will focus on both electrical and optical cable FACTs and will provide an overview of previous field experiences that led to the development of a modular FACT termination system, the design basis specification (10,000 psi) and the rigorous qualification testing program of the components, sub-assemblies and the FACT termination system. In addition, uses of this technology to date will be summarized, including projects in Brazil such as the Chevron Frade (electrical) and Shell BC-10 (electrical and optical).

1. 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. Experience with cable termination has shown that, depending upon cable construction, two failure modes are possible in deepwater applications. Firstly, the core element can collapse into an atmospheric breakout region resulting in push-back or bird-caging of electrical cables and fiber damage on optical cables. Secondly, there can be 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 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) embarked on an ambitious design program to eliminate the limitations of the current technology and increase the reliability of their terminations. The result of that 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. The second generation of this FACT technology, called FACT G2, which utilizes standard FACT components, allows factory build and testing of majority of the termination system before delivering to the field, thus significantly reducing operator dependence and termination time while increasing reliability. This paper will detail the common failure modes of earlier technology along with the mitigating remedies, review new technology for terminating cables for deepwater applications that eliminates known failure modes and provide the results of the qualification program of the second generation of new technology. In addition, the paper will review the track record for FACT technology.

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2. Failure Modes

2.1. Core Element Collapse

Core element 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 through 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. For an optical cable, the fiber tube is passed through a self-activating bi-directional elastomeric gland seal and then through a tube swage assembly that grips and seals the fiber tube. The fibers are sealed in a potting assembly called the optical gland fiber lock. As the volumes between the gland seals and nipple boot seals or tube swage assembly 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. For an optical cable, the fiber is fusion spliced to pigtails and managed inside the splice canister. Either a traditional bladder style compensator or radially compliant jumper hose provides pressure and thermal compensation of the dielectric fluid.

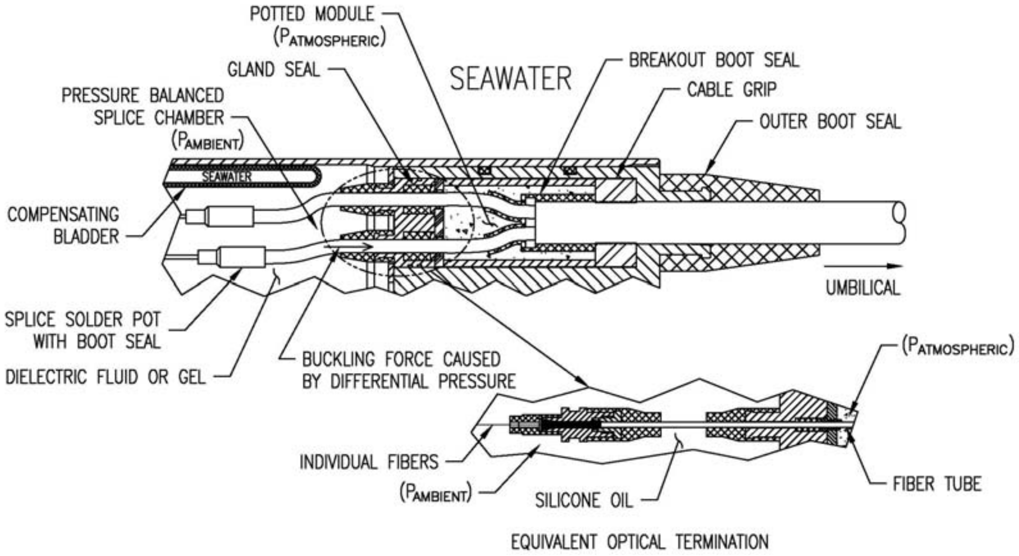

Figure 1: Conventional Cable Termination Assembly with Atmospheric Breakout Region (Potted Module)

Push-back is caused when differential pressure exists between the pressure-balanced splice chamber and the termination module. 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 splice chamber into the low-pressure potted module if the load exceeds the column strength of the element. This failure mode is typically associated with the conductor elements or fiber tube within the cable as they pass from the atmospheric potted module to the pressurized fluid-filled splice chamber. There is no exact way to predict how much conductor or fiber tube 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, possibly causing a short circuit or low insulation resistance condition. In the case of an optical termination, the spliced and managed fibers may experience compromise in their bending radius or strain on fusion splice joints possibly causing optics degradation or even fiber breakage.

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. In the case of an optical termination, the fiber tube buckles as a result of loads placed on the major element, as in the push-back case which results in damage to the fibers. This failure mode will most likely occur within the atmospheric region between the gland seals and nipple boot seals or tube swage assembly, but may occur along any loaded section of the conductor or fiber tube within the 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. In the case of the fiber tube, column strength of the core elements and sub elements are functions of many variables including, but not limited to fiber tube diameter, thickness, 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 this 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. For an optical cable, the ratio of the fiber tube diameter to tube thickness is the first order variable that determines the buckling resistance. As this ratio increases for a fixed fiber tube outer diameter (tube thickness decreases), the column strength of the fiber tube is substantially decreased. For an electrical cable, 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.

2.2. 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 seal that provides the primary barrier to water ingress. The armor from the cable is flared out and epoxy-potted to provide mechanical strength. The cable inner 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 hose provides pressure and thermal compensation of the dielectric fluid.

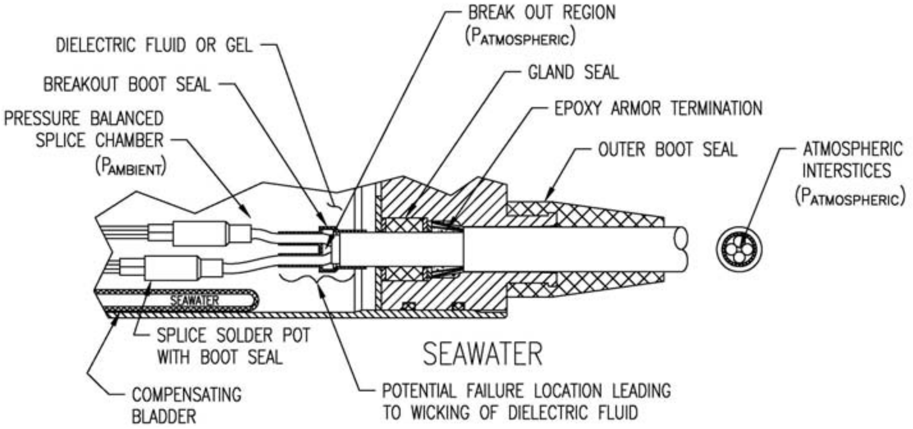

Figure 2: Conventional Termination Assembly with Breakout Boot Seal in the Pressure-balanced Region

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 is compromised. In an optical termination, the optical gland fiber lock, which is in contact with the pressurized compensating fluid, compromise will lead to wicking. 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, conductors themselves within the pressurized dielectric compensating fluid and the optical gland fiber lock, all have the potential to void the termination if compromised.

Wicking, in an electrical termination, 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 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.

3. 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. ODI believes that this understanding has lead to a design and qualification process that mitigates the risk of the failure modes described above. This is confirmed by 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 balanced 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 second generation of this FACT technology, called FACT G2, utilizes standard FACT components and allows factory build and testing of majority of the termination system before delivering to the field, thus significantly reducing operator dependence and termination time while increasing reliability. The details of the FACT technology and the FACT G2 are explained in the following paragraphs. Figure 3 shows the FACT assembly consisting of a high-pressure cable end termination assembly that completely isolates the electrical, optical and hybrid cable internals from the subsea environment and pressure-balanced splice chamber. The 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.

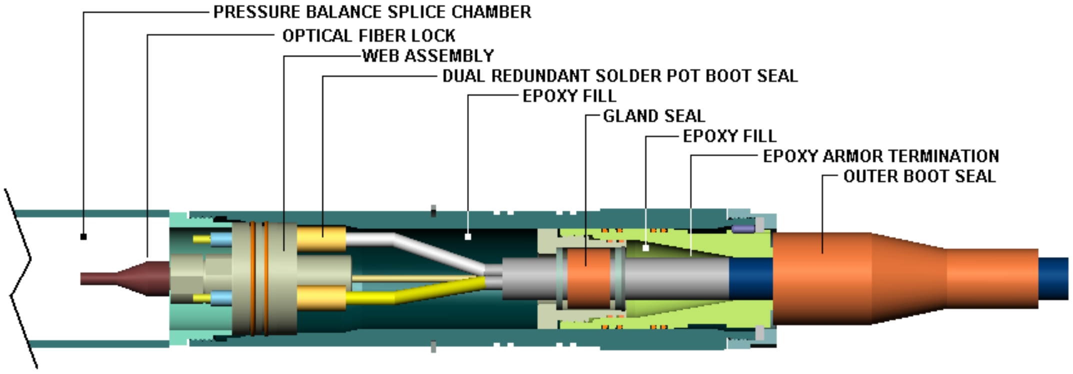

Figure 3: First Generation Field Assembled Cable Termination (FACT) Assembly
that isolates the cable from the pressure-balanced splice chamber

The individual conductors are broken out and interfaced to a high a pressure header "Web" assembly using dual redundant solder pot boot seals. All interstices within the assembly are 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. Figure 4 shows the unique elements of an optical FACT, patented tube swage to fix the fiber tube and fiber lock optical gland technology.

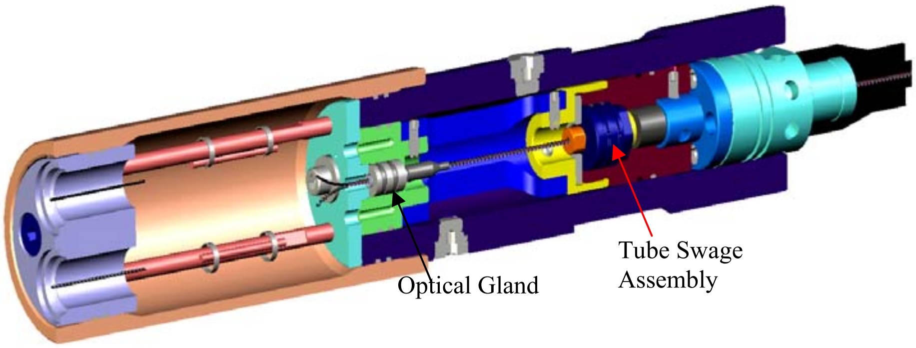

Figure 4: First Generation Optical Field Assembled Cable Termination (FACT) Assembly

The “Web” assembly isolates the internal cable elements from the pressure-balanced, dielectric fluid-filled splice chamber using field proven Nautilus Electrical pin technology. In an optical termination, the fibers are routed through a gel-filled atmospheric region before interfaced to the "Web" assembly. The gel acts as a dampening cushion to fibers which may otherwise move inward under pressure differential. The "Web" assembly for optical terminations contains ODI's patented fiber lock optical gland technology. The “Web” assembly has been rigorously qualified at differential pressures greater than 10,000 psi.

The FACT cable end assembly 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 assembly has been designed with modularity in mind and may be used with ancillary accessories to adapt to a wide array of interfaces. Additionally, the FACT assembly 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.

In the second generation FACT technology, called FACT G2, the "Web" assembly is integrated into the pressure-balanced fluid-filled jumper harness assembly. Due to this arrangement, the critical "Web" assembly can be factory assembled and tested before delivering to the field. This results in increased reliability and significantly reduces operator dependence and termination time. Figure 5 shows the G2 FACT component assembled in the factory and those assembled in the field. For comparison, Figure 6 shows a conventional crossover termination where both the fluid-filled hose and the termination are assembled in the field.

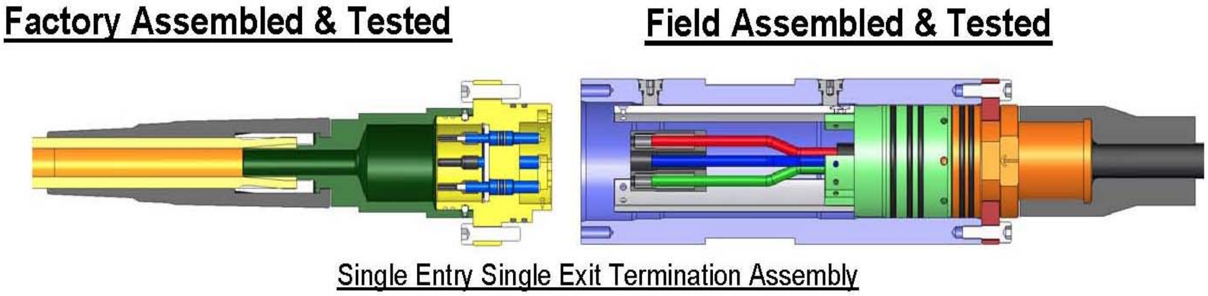

Figure 5: FACT G2 Assembly Factory vs Field Assembly and Testing

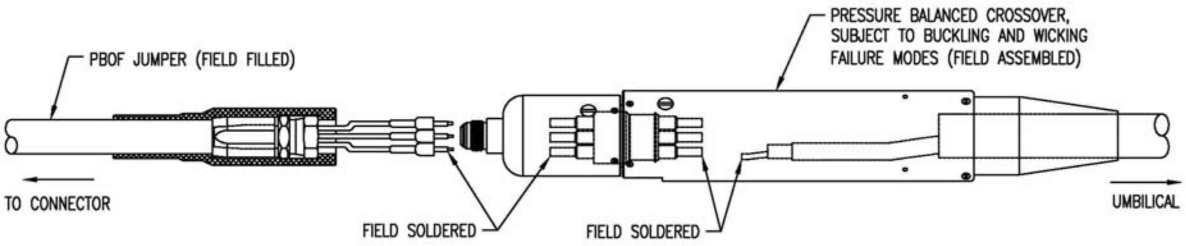

Figure 6: Standard Crossover Termination Requiring Field Assembly of Both the
PBOF Jumper and the Crossover FITA

Figure 7 shows the electrical and optical FACT construction. This design approach also gives the customer the ability to integrate the harness in advance (prior to umbilical termination) in their system to perform relevant verification tests. Apart from the above mentioned improvement, design enhancements were made in the FACT G2 technology to improve electrical performance, reliable optical fiber handling and management.

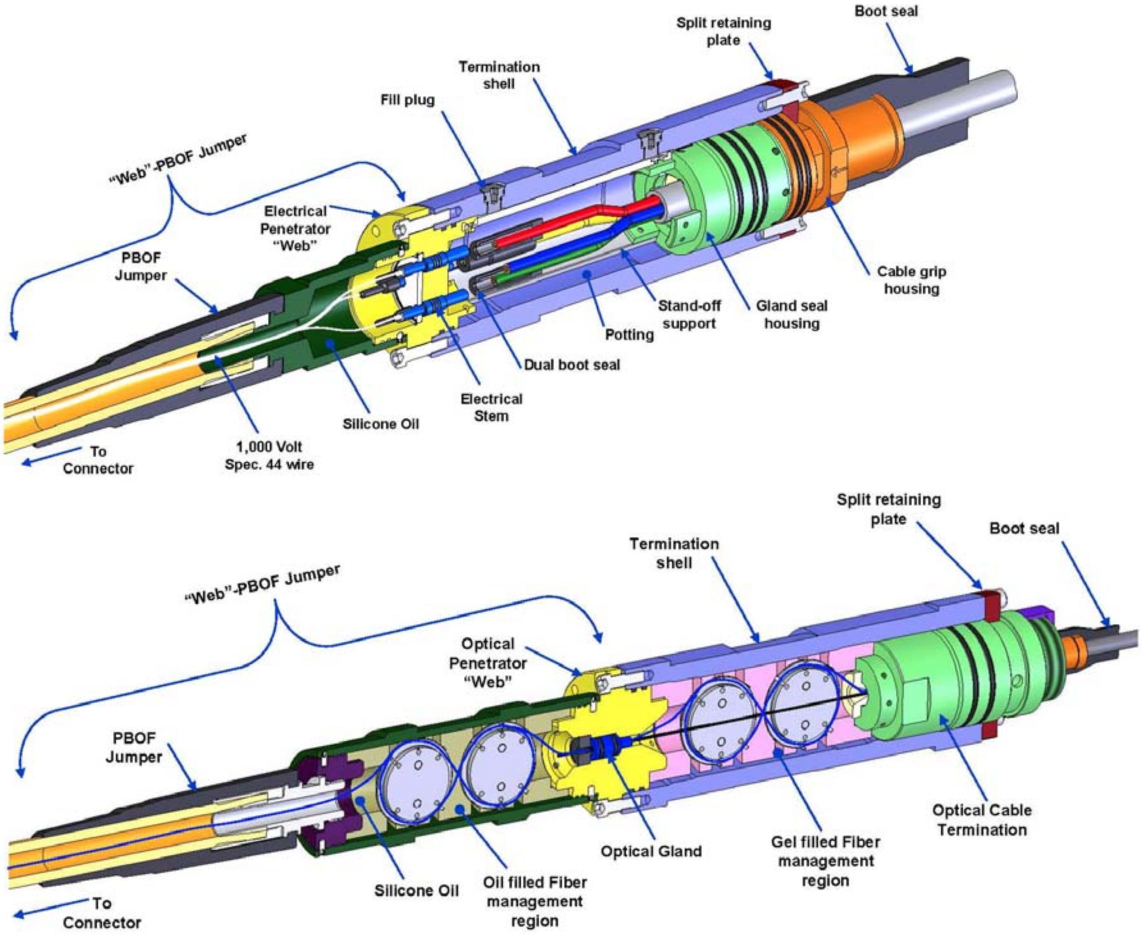

Figure 7: Second Generation Field Assembled Cable Termination (FACT) Assembly – FACT G2

4. G2 FACT Qualification Summary

The FACT G2 system was successfully qualified during the fourth quarter of 2007. This qualification program consisted of two elements: the high pressure header "Web" and complete FACT system assembly. This was done to qualify all of the elements including secondary and tertiary seals. The qualification test complies with industry standards, but not limited to, ISO 13628-6, IEC 60502-1 [17.3] and Norsok U006. Figure 8 is a flowchart of the qualification program for the FACT G2.

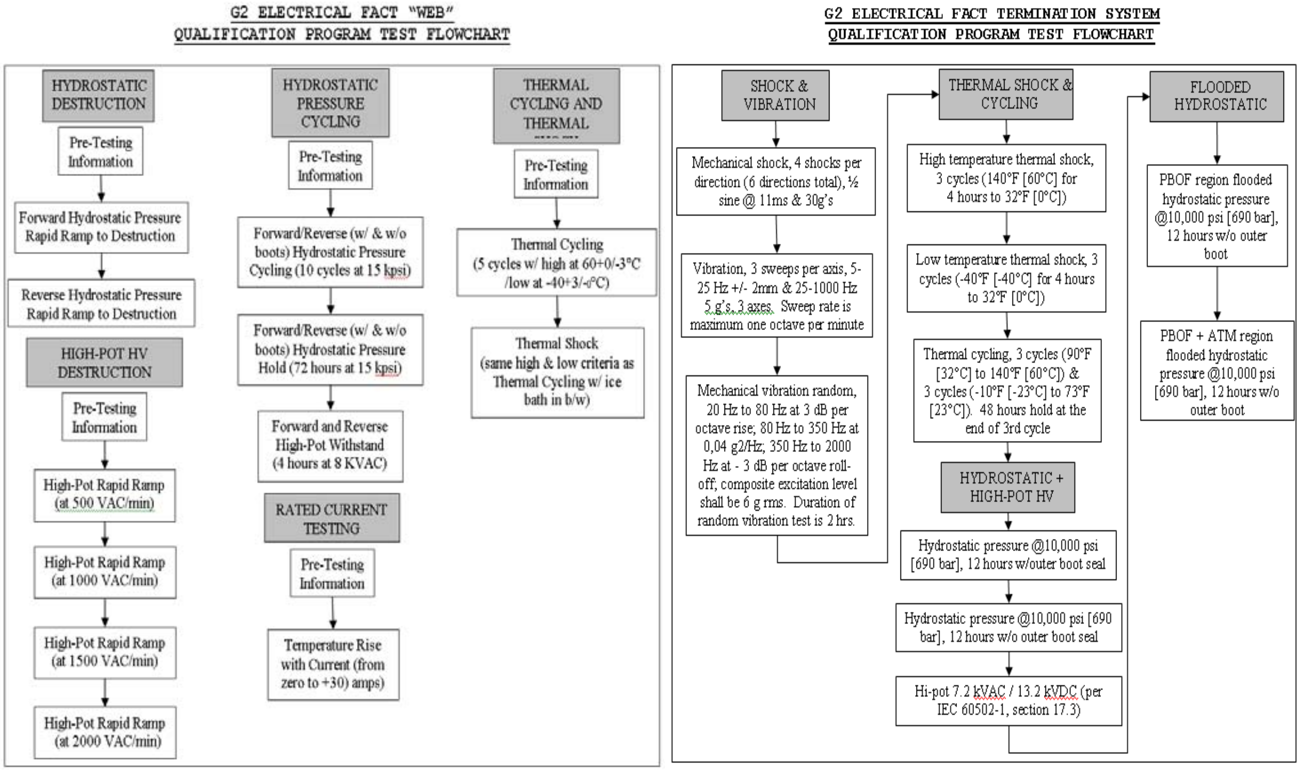

Figure 8: Flowchart of FACT G2 Qualification Program.

The FACT G2 qualification testing program was successfully completed, which verified the technical specification summarized in Table 1 below.

Table 1. Technical Specification for the Optical and Electrical FACT G2

Material:	Titanium Grade 5 (isolation from cathodic protection system required)	
	316L Stainless Steel (connection to cathodic protection system required)	
Circuit Configuration:	Electrical = 7 circuits per "Web" Assembly	
	Optical = 12 circuits per Optical Gland Assembly	
Maximum Cable Diameters:		
	Electrical FACT = Ø0.625" [15.8mm] to Ø1.27" [32.3mm]	
	Optical FACT = Ø0.3" [7.62mm] to Ø0.7" [17.78mm]	
	Hybrid Penetrator = TBA	
Pressure:	Max Operational Depth:	14,750 ft [4,500m] (With FOS of 1.5)
	Max Test Pressure:	10,000 psi [690 Bar]
	Web Qualification Test Pressure:	15,000 psi [1034 Bar](Electrical)
		10,000 psi [690 Bar] (Optical)
Electrical:	Maximum Operational Current:	30 Amps per Circuit*
	Maximum Operational Voltage:	1.8 Kvac/3.0 kVDC
	Insulation Resistance:	≥ 10 GΩ @ 1 kVDC*
	Splice Resistance:	≤ 0.1 Ω per splice
Optical:	Insertion Loss:	< 0.1 dB/splice @ 1310/1550 nm*
	Return Loss:	≤ -55 dB/splice @ 1310/1550 nm* (Excluding Connector)
Operational Temperature:	+13°F to +122°F [-10°C to +50°C]*	
Storage Temperature:	-40°F to +140°F [-40°C to +60°C]*	
Design Life:	25 years	
* Subject to cable performance		

5. Track Record

FACT technology was first deployed in 2005 offshore of West Africa. Table 2 summarizes the deliveries to date for the FACT product. Note that the actual subsea deployment date is typically 6 to 12 months after the product delivery. The FACT G2 was developed in 2006 with the first deployments in 2007.

Table 2. Project Delivery History for FACT Terminations.

Year	Number of FACTs Delivered	Average Water Depth
2004	37	1200 M
2005	35	1600 M
2006	314	1320 M
2008	334	1560 M

The first projects that will be deployed using the FACT G2 technology in Brazil are Chevron Frade and Shell BC-10. The FACT solution was recommended and accepted for the Frade project because of the project's water depth and the field's ringed architecture which resulted in up to 13 cable terminations in series. The FACT solution was recommended and accepted for the BC-10 project for the following reasons.

1) Project design pressures of 300 bar (~4500 psi) increases potential for cable element failure modes.
2) The field architecture results in multiple connections in series.
3) The large cable element cross section of a 10mm² core with Ø 0.238" (Ø 6mm) insulation increases susceptibility to cable element failure modes.

BC-10 will also be the first deployment of an optical FACT in Brazil.

The first subsea installations for both Frade and Shell projects will be completed by the end of 2008.

6. Conclusion

While the traditional FITAs (Field Instable Termination Assemblies) have proven reliable in many applications, ODI's deepwater termination experiences have shown the potential for problems. Eliminating the complex interactions between the internal cable elements and pressurized fluid interfaces is important as more complex cable terminations, such as high voltage and optical applications, are deployed in deeper waters. The FACT technology provides the necessary cable isolation to ensure a highly reliable termination to support these future generation ultra-deepwater developments. The second generation product, FACT G2 was developed to enhance reliability by maximizing factory assembly and testing while minimizing field assembly steps. Qualification testing and field experience have verified FACT technology for high reliability applications in ultra deep waters.

7. References

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