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Breaking The Cycle Of Submarine Cable Failures and Enabling Future Systems through Optical Fibre Architecture

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***Abstract*— Forensic study of submarine cable failures reveals material choice, manufacturing processes and, significantly, quality controls all have the potential to introduce failure modes.**

Selecting the right materials and manufacturing processes is at the heart of a fit and forget system where 30 years life with zero leaks is required. In addition to mechanical adhesion, chemical bonding between materials at molecular level is essential for achieving long-term sealing. Materials offer different properties; their bonding requiring disparate degrees of specialist chemical and processing knowledge. One polymer is notoriously difficult to process and bond; the other is slightly hygroscopic, absorbing moisture at a rate which increases as temperature increases. Platforms fitted with the latter typically have planned replacement programmes at every refit providing a lucrative resupply market at odds with resolving the engineering challenges which result in its short life expectancy. The former is not so affected.

The study reveals how some test and inspection protocols relied on to offer the quality assurance requisite for first-level items may create false confidence about product life. Radiography used to demonstrate moulded cable integrity utilising processes used for x-raying metallised components provide images that do not reveal potential problems. Only specialist, low power radiography profiles the chemical bonding at molecular levels to identify bond failures which will eventually create leak paths for water ingression resulting in performance degradation or critical failure.

The study reveals how the pitfalls of the past can be avoided and essential systems safeguarded, and how optical fibre systems are providing the bandwidth to optimise future system performance.. (Abstract)

Keywords-cables; harnesses; pressure-hull glands; moulding; fit and forget

I. Introduction

A combat, sonar or propulsion system is only as good as the infrastructure connecting it; why then, 300 years after the first military submarine was built, are some platforms still seeing system failures relating to cable infrastructure whilst others have cabling systems performing after decades at sea.

This study by SMI looks at how complex technologies understood for over half a century are still being misapplied to naval defence applications with catastrophic, yet predictable, outcomes for platforms.

SMI was founded over 25 years ago by engineers at the forefront of subsea cabling development, initially for fibre optic telecommunications and thereafter for the UK's Royal Navy. Today SMI has perfected these technologies for use by navies around the globe producing critical cable architecture that forms the backbone connecting platform systems. Whilst some of the technologies supporting innovations for future capability date back to the 1930's, newer developments deliver higher data-rates and bandwidths in support of the submarines, surface ships, and bottom-mounted arrays currently in design. With cable harness technology evolving, and new players in the field, it is difficult to accept the cycle of failure which sees the shortcomings from the 20th century being replicated in current fleets. To break this cycle it is necessary to understand why failures occur and where prevention can be applied.

II. Material Selection for Cables Harnesses

Subsea cable jackets are generally made from two groups of materials: thermoplastics and rubbers.

The majority of thermoplastic cables have either polyethylene or polyurethane jackets, where granules of the material are melted and extruded to form the cable jacket. Synthetic rubber cables are often jacketed using polychloropene (neoprene) which is cured using a vulcanisation process. Polyurethane is also supplied in a thermoset form, comprising a liquid resin and separate hardener, which when mixed together form bonds between atoms in the carbon chain, the basic building block of polymeric materials. Another thermosetting material is epoxy, which is also supplied in two fluid parts that when mixed and cured offer advantages over thermoset polyurethanes in stiffness and ability to withstand temperature.

Each material has advantages and disadvantages, and their effective use depends on in-depth knowledge of their properties. The expertise required for getting it right first time has been significantly diluted since the 1960s, when the core technology was proven and established in UK submarines for the first time. The cynicism [1] which met the 1968 publication of "Polyethylene Bonding to Metal for Cable Penetration of Pressure Hulls and Communications Applications" by Lenkey and Wyatt [2] pervades today, especially in the US where this mastery of this particular technology remains elusive. As late as 2018 one major US manufacturer conceded that PE was the optimal choice for subsea moulding techniques [3].

A. *Polyethylene, Polythene (PE)*

Invented in 1933, PE is a thermoplastic that is only supplied in granular form. It has a unique combination of excellent dielectric characteristics (particularly at high frequencies), high electrical resistivity, low moisture permeation, and low water absorption.

As evidenced by the man-made plastic pollution of the oceans, PE does not degrade over time. Cable-grade polyethylene is effectively inert in the ocean. Processes such as oxidation, hydrolysis (chemical breakdown in water) and mineralization are extremely slow with polyethylene jacketed cables having now survived for more than 40 years immersion in sea water. Furthermore leading polymer scientists [4] advise that the total conversion of polyethylene to carbon dioxide and water will take centuries.

PE delivers orders of magnitude better insulation resistance than other materials, and this performance does not degrade at higher operating temperatures. Crucially, PE does not absorb water or moisture over time as other materials do, which is what makes it the only jacket material that can deliver 30+ year sealing performance. PE expands and contracts volumetrically by more than 30% when heated to melting point and has a very low thermal conduction coefficient. This makes it notoriously difficult to process, and its low surface energy makes it very difficult to bond to any other materials. A consideration highlighted by Berian [5], "When specifying or selecting a jacket material foresight should be given to the termination procedure… the bonding procedure should be established."

Carter L., Burnett D., Drew S., Marle G., Hagadorn L., Bartlett-McNeil D., and Irvine N. [6] observe that "the effects of ultraviolet light (UV-B), the main cause of degradation in most plastics, are minimized through the use of light-stabilized materials, …and the natural reduction in light penetration through the upper ocean, where the photic zone rarely extends beyond 150 m depth."

Specialist knowledge of the chemistry and compatible processing technology is needed. In general epoxies, polymeric and rubber materials do not bond well, or at all, to polyethylene. There are processes being used which are difficult but do control and guarantee repeatable performance. Therefore, the general good practice of not mixing different materials is especially the case with PE. Nevertheless, with the right knowledge and processes for PE, exceptional bonding can be achieved to metals and rigid polymers. This is the basis for SMI 23 years of capability approval for the supply of pressure-hull glands to the UK Ministry of Defence (MoD). SMI is the only remaining manufacturer of PE pressure hull glands. No other company has achieved capability approval to Def Stan 08-171 from MOD.

B. *Thermoplastic Polyurethane (TPPU)*

TPPU is another thermoplastic material also supplied in granules that are melted and injected to manufacture cable jackets. TPPU is a viscous elastomer, which means it has greater elasticity than PE and this offers different performance and properties. TPPU is not suitable as an electrical insulation material but has some outstanding properties as a cable sheathing, making it suitable for high performance electrical cables in the most challenging of environments. It is very flexible throughout a broad temperature range, typically between -40°C and +125°C. TPPU sheathing is extremely wear-resistant and mechanically tough – it's very difficult to cut or tear. It also has excellent ageing resistance against environmental humidity, ozone, UV radiation and microbes whilst offering an excellent barrier to a wide range of chemicals and oils. A useful characteristic of PUR as a sheathing material is its anti-kink property, making it ideal for flexible and retractable cables.

TPPU is marginally hygroscopic and absorbs moisture at a rate of .3% to 1% by weight which increases as temperature rises. We have observed more rapid TPPU insulation resistance degradation in ships' bow sonar cables, especially when used for active sonar in the warm waters of the Gulf. Investigating his phenomena when evaluating TPPU as a thermal insulator for the Oil and Gas industry, Le Gaca, Choqueusea and Melotb [7] determined that a commercial polyurethane aged for more than a year in natural sea water from 25°C to 120°C absorbs about 1.8% of water and undergoes hydrolysis at high temperature.

C. *Thermoset Polyurethane (TSPU)*

Polyurethane, unlike PE, can also be supplied as resin and hardener that permanently cures when mixed together. The good mechanical properties that are delivered in the thermoplastic TPPU version are not retained in the thermosetting TSPU. Water absorption of TSPU is greater than 4% which, combined with a lower dielectric strength, reduces the life of TSPU terminations. It is easy to mix and pour into low cost tooling which makes it inexpensive and easy to set up. Nevertheless, TSPU relies on largely mechanical adhesion to the cable jackets, connectors and gland stems, and will not last for any extended life in sea water. This is because mouldings relying on mechanical adhesion only are weak and susceptible to delaminating at the interface with the cable jacket and the gland/connector.

D. *Polychloroprene*

Commonly known as Neoprene this synthetic rubber is widely used for low cost cable jackets and can be used for O seals. Neoprene is only suitable for up to five years immersion and has low insulation resistance performance. Haworth [8] concedes "neoprene-to-metal bonding technology is widely used and well advanced in this country (USA) Neoprene does not possess the dielectric and low water absorption properties of polyethylene." The oils used in the manufacture of rubber material can be attacked by subsea microbes and we have witnessed rapid degradation in operational performance especially when operating in warm sea conditions. Neoprene should never be used for O seals due to its poor long term performance in sea water.

E. Epoxy Resin

Epoxy resins offer good bonding to metallic and technical plastics, exhibit good mechanical strength, stiffness and resistance to sea water. They are widely used to water block connectors and glands but in general do not bond well to wire insulation or cable jackets. A fundamental of good termination design is to have the rigid material internally and the flexible material on the outside of the termination. The effect of hydrostatic pressure therefore works with the design to squeeze the flexible moulding onto the stiff substrate to eliminate any peeling of bonded interfaces. It should be noted that in the reverse case, if resins are used externally to seal to a cable jacket, the stiffness of the resin and the hydrostatic pressure on bonded joints results in high peel stresses, a very undesirable state which increases the probability of delamination.

III. Dual Jackets and dual sealing

Cable jacket selection has historically required a compromise between electrical performance and abrasion resistance. While ideal for service, PE is not the best material for resisting the often non-specified hostile dockyard environment.

Increasingly dual jackets are being specified to guarantee robustness during build and long life in service. However it not sufficient to simple have sheaths in both PE and TPPU to realise the advantages of both materials the jackets need to be separately water blocked and bonded.

This technical solution of SMI PlastEthUrm™ dual sealing is so robust that PE/TPPU cable harnesses are now offered with a standard guarantee against leaks of ten years from immersion reflecting the confidence that comes from more than 10,000 installations with zero leaks.

IV. Bonding and Amalgamation

In order to make informed decisions relating to fit and forget performance of cable systems for outboard submarine hostile environments, it is crucial to understand the basic science applied to adhesion and polymer processing. Sealing is provided by the cable jacket and the termination moulding. Using the best materials for both is a fundamental aspect for delivery of long-life sealing. Again Haworth [8] recognises this nearly half a century ago, "Cable seal failure after a design has been adequately tested and proven can be traced invariably to poor bonding."

In addition to mechanical adhesion, which relies on roughening the adhering surface to increase surface area and interlocking, chemical bonding provides a very high strength union, guaranteeing the best long-term resistance to water penetration at molecular level. Chemical bonding occurs when the atoms of adjacent materials containing free electrons and electron holes in the respective outer shells, are encouraged to transfer across, to achieve a lower state of equilibrium, resulting in a chemical bond. This can only happen when sufficient energy is introduced to excite the free electrons resulting in transfer to the adjacent electron holes in the other material. By definition, the bond will be stronger than the weaker of the two materials and orders of magnitude greater than any mechanical joint. High pressure and temperature provided by the thermoplastic moulding process provides the energy required for this bonding to occur.

Another important property of thermoplastics is they can be re-melted many times. This is what happens to the granules when heat is added to transition from solid to molten form, before it is injected under high pressure into a tool, to manufacture a termination. The cable jacket is also melted during this process and so all the material mixes and flows together so that it cools into a completely homologous material. Effectively, the cable jacket shape is tailored to incorporate the profile required for the termination without the need for any join or interface. The picture in Figure 1 shows a perfect example of amalgamation with the injected PE material (white) mixed together throughout the moulding, with black PE originating from the melted cable jackets. This demonstrates the scale of amalgamation achieved during the process.

Figure 1. Example of PE cable and mould amalgamation.

This amalgamation process is absolutely key to long-term sealing, as with no interface present, water can never enter a thermoplastic moulding at this critical junction.

A. Functional Performance Attributes

Water blocking is applicable to connectors, glands and cables. In the latter it is achieved by filling the interstitial space in the cable with a material which is intended to prevent water from travelling along the cable. These fillers work best on very long seabed cables where hydrostatic pressure is constant. Due to the pressure cycling that occurs with a submarine, water blocking can never be achieved other than reducing the rate of water propagation along the cable. If there is a screen present this will be even less effective. The approach for submarines therefore must be to guarantee sealing of the cable jacket, which must be as robust as possible to deliver reliability over the whole life of the submarine.

In the case of glands and connectors, water blocking is often achieved by the use of epoxy resin which when applied correctly will prevent any water molecules passing through. This is important for connectors to avoid any corrosion of the connector contacts in mating receptacles and in glands prevents water ingress into the submarine. Non-cross hosing is critical to retaining reliability in multi-cable terminations which can have up to 20 separate cables entering a gland or connector. To restrict the catastrophic impact of water leakage through damage of a cable jacket, the termination is designed and manufactured so that water is prevented from tracking across internally between any and all of the adjacent cables. Therefore, all the functionality is retained in the system except for the single cable that has been damaged.

In the UK the importance of non-cross hosing is addressed through specific tests in the MoD capability approval for the production of pressure hull glands, recognising the criticality of each cable integrity. The capability tests, which are requalified by manufacturers every three years, are the bench mark for precluding leak related cable failures. A regime of re-approval ensures that the supply chain retains its technical capabilities long after initially satisfying the standard. This is another approach which can break the cycle of failure.

B. Cathodic Delamination

Cathodic delamination is a process in which a polymer debonds from a metal surface in the presence of a cathodic protection system. Impressed current and sacrificial anodes used to protect submarines structures can present problems to anything that is bonded and located in the immediate vicinity.

The is a plethora of academic study [10-17] into cathodic delamination recognising that electrochemical reactions taking place at the metal- polymer interface cause separation of the materials. Influential factors include type of metal substrate, composition of electrolyte, electrochemical potential, coating characteristics and oxygen levels [12-17].

Manufacturers have therefore been able to develop designs and processes which mitigate or eliminate this phenomenon and cathodic delamination is no longer considered the problem for submarine cable connections it once was, that said, with failures in service still being traced to cable leaks it can be surmised that not all manufacturers have cathodic delamination under control.

C. Testing and Inspection Regimes

In addition to hydrostatic pressure testing including cycling, routine radiographic inspection is industry best practice for guaranteeing the integrity of mouldings. Prior to acceptance, three axis non-destructive x-rays are used to prove the quality of the moulding and establish that bonding across the whole adhered surface has been achieved. This process makes it possible to identify any potential source of in-service failure.

The industry has long drawn comfort from receiving tested and inspected products purporting to offer the quality assurance associated with first-level items. Whilst it is clear that the routine tests of electrical and optical systems and hydrostatic testing remain the most important post-production test, some of the other inspection activities used to bolster confidence may have been creating a false conviction about expected product life.

X-ray imaging techniques employed for many years in the non-destructive defectoscopy inspections of composite materials intended for the Aircraft industry are being applied to cable mouldings for marine applications. Low and high energy Real Time Radiography (RTR) can be used to for defects visualisation and delamination detection.

The unit of density variance between two areas on a radiograph referred as radiographic contrast. In order to differentiate areas of interest in the X-ray, such as defects or cracks from the surrounding metal or polymer background area, contrast became very helpful. A low energy which below 70kV X-ray beam tangentially illuminates the “horizon” of the material under test such as pipe [9]. Radiation is detected by an image intensifier, upon which voids or bond failures cause a “shadow”.

Utilizing a higher power X-ray typically associated with the interrogation of metal components fails to generate the required contrast to illustrate these defects. Evidence shows that some components supplied with the requisite radiographic imagery created at higher levels will present as flawless but will contain bond failures illustrated only by lower power x-ray levels; failures which will over time create leak paths for water ingression resulting in performance degradation or critical failure.

Standards are being revised to reflect these techniques but only by an industry-wide transition in process can restore confidence in radiography as an assurance tool.

V. CONNECTORISED PENETRATORS VERSUS PRESSURE HULL GLANDS

There has been a move in the last two decades towards modular build programmes which introduce manufacturing flexibility. This build approach sometimes calls for connectorised penetrators. There is an argument that if the connectorisation were inside the hull, this would make maintenance and replacement very much easier and cheaper. But the operational preference is to have the connectors external to the pressure hull. This means that the reliability of the harness is potentially reduced by the performance of the sealing of the connector as well as the effectiveness of the terminations.

Historically pressure hull glands were preferred. Connectors on either side of a hull penetration introduce additional potential fail fields at the interface and the cable termination so a pressure hull gland inherently attracts less risk. There are pressure hull glands in service now some 30 years after installation with performance at near new levels and surpassing expectations.

With platform systems increasingly generating and consuming more data, the need for power and data bandwidth has increased exponentially. Taking additional services through the pressure hull requires additional penetrations each a critical, first level risk. If each of these has a connectorised penetrator the risk level is further exacerbated.

Two strategies can be employed to de-risk modular build whilst supporting future capabilities. The first is migrating data from copper to fibre media and the other is to put multiple services through a single penetration without adding additional connectors. Multi-Gland Penetrators (MGPs) have been developed to increase the service density through a single penetration on the hull exploiting the tried and tested pedigree of pressure hull glands whilst satisfying the build flexibility

Figure 2. Multi Gland Penetrator

VI. Optical Fibre

The complexity of electronics developed for advanced technology weapons systems relies on fast information exchange, operating at maximum efficiency. Historically this information is transferred back and forth between complex systems through a maze of heavy cabling, requiring numerous hull and bulkhead penetrations and junction boxes.

The use of optical fibre on surface fleet to provide the necessary bandwidth and replace extensive copper cabling is well established. There are additional challenges which have hitherto prevented the widespread deployment of optical systems on underwater platforms, most notably, successfully managing optical continuity through penetrators. Working with key stakeholders SMI has developed optical multi penetrator technology which offers the reliability of legacy systems with the capacity to support future electronics.

The successful introduction of multiplexed data networks based on a modern fibre-optic technology for future platforms affords an opportunity, whilst increasing functionality, to rationalise cable runs and penetrations, further reducing the likelihood of leak associated failures.

VII. Commercial Considerations

The UK National Audit Office (NAO) criteria for assessing the value for money (VfM) of government spending include 'the three Es': Economy, Efficiency and Effectiveness. All too often, only economy, i.e. the initial capital cost, is recognised and evaluated. In the case of submarine cable harnesses, efficiency would encompass reliability and through life cost for maintenance and replacement, and effectiveness would require systems to deliver the bandwidth, power and system support required by design throughout the life of the boat. Any erosion of efficiency and effectiveness rapidly decreases overall VfM even if economy is very strong.

The Royal Netherlands Navy is the first in the world to apply through life costing to the initial build of its new boat in the Walrus class replacement.

Separation of initial capital investment and operational costs into different government funding schemes and budgets has traditionally disguised the cost of replacing failing cables, allowing poor technical selections to be made based on initial economy but carrying a lifetime of replacement burden and repair costs which fail to deliver value for money; manufacturers profiting from poor product supply.

Failing cables have driven a thriving economy with some manufacturers able to produce cables time and again, replacing repeatedly as leaks occur and failures result. With essential navigation, sonar and weapons systems repeatedly falling out of service – there's no other option but to replace cable sets. The US navy regularly replaces critical sonar cables at least every 7 years.

If routine replacement of cable systems can be eliminated through the choice of materials, there is an opportunity to greatly increase efficiency with a relatively small impact on economy.

Tired of being hostages to fortune and with Defence budgets across the world under pressure, astute naval engineers are now evaluating based on through life costs, looking for fit and forget solutions which remain reliable throughout the life of the platform.

Likewise, reliable performance from cable systems to deliver the full capacity of the systems they support will greatly increase their effectiveness. Appropriate radiographic inspection provides a further level of assurance at costs negligible compared to those associated with in-service failure and could be inexpensively introduced to support a service life in excess of 25 years.

VIII. Conclusions and Recommendations

To break the cycle of submarine cable failures lessons must not only be learned from history but changes in approach adopted to preclude recurring failure patterns.

Understanding the impact of cable jacket material choices on the long term durability of the system and insisting on cable termination practices qualified repeatedly to exacting standards is the first step in moving towards a failure free expectation from cable systems.

Inspection techniques should be appropriately applied to deliver the assurance they purport to offer and greater refinement of defence standards can ensure that these techniques are more consistent across the supply chain,

Architects can achieve the service density they desire, by adopting multi gland penetrations and optical fibre systems, without the need to forfeit reliability.

Through life cost assessments demonstrate the VfM of engineering decisions previously deemed uneconomic. Alternative strategies considered to offer value on build have been demonstrated to introduce inordinate costs through failure.

If these elements are well understood and applied, defence organisations can rightly demand extended warranties for submarine cable systems instead of relying on the rather esoteric notion of a design life. SMI already offers a 10 year warranty on PlastEthUrm™ mouldings.

Sufficient evidence exits to begin to cure the malaise of submarine cable failures and deliver cable infrastructure for the future demands of the underwater over the life of platforms.

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