ESCAPING THE SHACKLES OF LEGACY ENGINEERING – A FRESH LOOK AT SUBMERGED EQUIPMENT MECHANICAL DESIGN

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Abstract: It is true to say that little has changed with regards to repeater and branching unit mechanical design over the last 30 years. Much of the mechanical design impetus has and continues to occur only through need, change typically responding to transmission technology advancements and their new found sensitivities and limitations.

The move from analogue to optical amplification in the 1980's brought new requirements for fibre strain management in cable, jointing and repeater interfacing, followed closely by the necessity to develop new sealing technologies to improve the hermeticity of housings and reduce hydrogen induced loss to name but a few.

At the time of these major changes in repeater design the choice and availability of suitable materials was limited for subsea application and cables were significantly larger and heavier, with very little commercial pressure to optimise steel or copper content. The lack of a clear design driver such as strength to weight and use of excessively conservative safety factors due to perhaps a lack of confidence in material quality led to the generation of repeaters that were on the whole over-designed.

By taking a blank sheet of paper and combining this with a "why not" approach, it is possible to deliver innovative Repeater and Branching Unit designs that push the mechanical design envelope and reset the benchmark mark in the industry.

This paper shows that by careful and inspired material selection significant improvements can be made in cable catenary management during deployment, the hermetic sealing and the thermal management of the opto/electronics. Such changes can be made without compromise to the strength to weight performance of the mechanical protection, thus delivering attractive opportunities to the market.

1. INTRODUCTION

The choice of suitable materials for telecoms submerged equipment is often a balance of conflicting properties to meet a kaleidoscope of "in service" requirements. Traditionally high tensile steels and copper-beryllium alloys (BeCu) have in the main been the staple choice for the external mechanics. However these come at significant penalty of weight, additional corrosion coating requirements for steels and careful machining considerations when processing beryllium. Titanium was considered as early as the 1980`s as a viable wet plant material only being discounted at that time due to limited availability of suitable alloys and resulting high cost

Today is very much a different story. Alternative materials such as super duplex stainless and titanium have been rapidly adopted by the Oil & Gas and subsea science communities following significant development in alloying and heat treatment. This combined with alternatives in thermally efficient high voltage insulators, advances in metal seal design and the growing use of glass to glass sealing as a replacement for glass to metal technology provides mechanical engineers with an opportunity to match the challenges demanded by new systems.

Figure 1 Titanium branching unit and 6 fibre pair repeater

2. MATERIAL CHOICES

The emergence and growth of titanium alloys in the oil and gas plus subsea science sectors leads to a natural progression for repeater design. As cost and availability become stable and competitive, attention is drawn to addressing the balance of conflicting properties to meet "In service" requirements. Grades 5, 25 and 28 were initially considered and compared with Be Cu and high tensile low carbon steel.

Cost and availability

Grade 5 comprises of 6% aluminum, 4% vanadium, and forms the staple alloy for both aerospace and subsea communities.
Grade 25 comprises of 6% aluminum, 4% vanadium plus 0.3% to 0.6% nickel, 0.04% to 0.08% palladium. The mechanical properties closely match those of Ti-grade 5. This material maybe considered for use in sour water applications such as the Black Sea to offset potential hydrogen embrittlement, however no costs were available at the time of writing. Grade 28 is a 3% aluminum, 2.5% vanadium alloy and has the addition of ruthenium, which help reduce cost as it is a cheaper filler, but also improves corrosion resistance. This material was developed in the late 90's for use in critical subsea components; however it is sadly now commercially unavailable.

The cost for grade 5 alloy, in the last 5 years has reduced. In 2008 aerospace grades were selling at up to £40-£55k per tonne, with commercial grades selling at £30-40k per tonne. Currently aerospace material prices are centered around £30k per tonne, with commercial grades reduced to around £20-24k per tonne. Such prices seem exceptional and supply is the key here. Many mills in Russia have closed their order books and the majority of supply is now emerging from China. Strategic and geographical positioning of supply now form the best opportunity for future cost saving. The costs quoted above for titanium are based on international supply and may well be lower for those manufacturers who have access to Chinese domestic markets. In comparison typical costs for beryllium copper grade 17200 have moved little in the last 5 years with typical prices at £30K /tonne rising from 28.5K/tonne in 2008 with higher engineering grades likely to demand extra cost premium. In comparison steels such as AISI4145H are much lower in price at £1500/1600 per tonne with prices rising last year around 15 to 20%. Here again additional cost premium is expected if a modified or enhanced composition on the basic material is required for low temperature embrittlement resistance and as such lead times maybe extended if order quantities do not meet the requirements of a full furnace melt, resulting in queuing at the mill. It is also noted that such materials require additional processing such as coating to prevent corrosion for steels and fume extraction/closed cell machining for BeCu and once again carry further added cost. Regardless of material type trends in subsea material pricing look to move upwards as world resources become more limited.

Comparison of mechanical and physical properties

If we compare the basic mechanical and physical properties of the three major industry preferred materials as shown in table 1 we see that there is an obvious cost advantage for steel even when coating and additional processing is factored in, however its

Material	0.2% yield strength Mpa	UTS Mpa	Hardness HRB	% Elong	Charpy Impact J	Density g/cm3	Thermal conductivity W/(mK)	Price/Tonne GBP	Specific strength KN.m/Kg
AISI4145H	825	960	350	13	28	7.85	53.7	2000	122.3
BeCu 17200	900	1140	340-390	10	16	8.36	65.8	30000	136.4
Ti Grade 5	828	895	363	10	17	4.43	22.5	25000	202.1

Table 1. Comparison of Mechanical and physical properties

strength to weight or "specific strength" is only 60% of titanium grade 5 . BeCu continues to be the least attractive material when mechanical properties are included, again here specific strength is a little better than steel at 67% of titanium whilst thermal efficiency is double that of steel and four times that of titanium although the cost to achieve this is signifcant. From a titanium perspective the specific strength advantage is obvious and is further amplified when considering the effect of the lower repeater weight in water (see table 2) and its beneficial influence on the deployment/recovery dynamics as covered in section 3 of this text.
With a titanium repeater typically being half the weight of similar competitor products (in some instances providing a saving of >200Kg per repeater excluding transport packaging) significant saving can be made on shipping and freight costs as well as allowing for lighter weight jigs and fixtures and simplified shipboard, equipment and handling.

Main Housing Material	Fibre Pair	Housing Dia (mm)	Housing Length (mm)	Approx. Weight in air (kg)	Approx. Weight in water (kg)
Steel	6	266	1129	444	341
BeCu (Style A)	4	343	1070	295	204
BeCu (Style B)	4	265	1400	520	380
Titanium (lightweight)	6	220	895	200	146
Tiitanium (armoured)	6	220	895	225	171

Table 2 Comparison of typical repeater weights

The obvious negative here is the much lower thermal conductivity which leads to questions over heat dissipation from the internal electronics and ability to maintain good thermal control over critical components such as pump lasers to avoid over life. This is considered later in this paper and alternative novel solutions have been found to offset this.

Natural corrosion resistance

Like BeCu, titanium offers a natural oxide based corrosion resistance removing the need for additional coating or process unlike that necessary for steel based housings and mechanics. One major problem for a totally titanium solution is the ability to integrate to steel cable armour without inducing corrosion through dissimilar metals. Whilst some suppliers adopt a non-metallic approach to armour termination and coupling protection it is still possible to maintain the parent strength of a high tensile steel interface by isolating the different metals. By isolating the steel termination housing from the titanium bend limiter the corrosion current in the Ti/Fe cell in sea water has been measured (See figure 2) as 1.75mA at 18°C, and less at lower temperatures. For a valency of 4, this will result in the oxidation of no more than 6.9gm of titanium per year, or 172gm over the full

25-year system lifetime. The steel in the vicinity of the titanium is therefore inhibited from corroding by the presence of the titanium.

Figure 2. Termination /coupling cell corrosion test

3. IMPROVEMENTS IN MARINE HANDLING

It is self evident that a smaller form factor housing will provide improved plough handling. With a smoother repeater transit through the plough bell mouth and with a reduced diameter the repeater will sit much lower in the repeater flaps on the back of the plough share, optimising its presentation to the depressor arm and resulting in improved control on burial. The primary advantage comes however not through size but through the reduction of weight.

During cable installation, whilst slack cable laying, it is a well-known phenomenon for the repeater weight in water to disrupt the cable catenary and efforts to mitigate the effects historically have involved all manner of measures to attempt to balance out the higher sink rate of the repeater in relation to the cable. By adopting a small form factor repeater structure that is predominantly titanium we effectively have a repeater that is approximately 220 Kg in air and around 146 Kg in water.

The model

Using the appropriate weights and dimensions taken from the relevant manufacturers marine installation guidelines a comparison of performance was undertaken by Makai simulation of 4 repeaters in a typical light weight (LW) cable section installed in a constant water depth of 6000m followed by a second simulation of 5 repeaters laid with variable bottom profile.

The cable lay was simulated at a constant speed of 8km/h. repeaters 1&2 were a titanium six fibre pair type. Repeater 3 was a four fibre pair steel repeater of similar dimensions, whist Repeater 4 was a typical four fibre pair repeater of BeCu construction. In the down slope simulation repeater 5 was again of titanium six fibre pair construction. Figure 3 shows the sample straight line diagram (SLD).

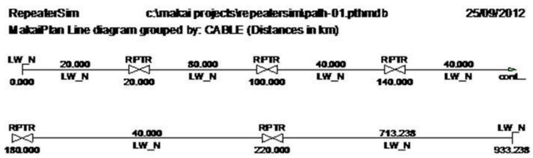

Figure 3: Simulation SLD

Constant depth deployment

Figure 4 clearly shows the difference in bottom slack and bottom tension for the first scenario in a constant water depth of 6000m.

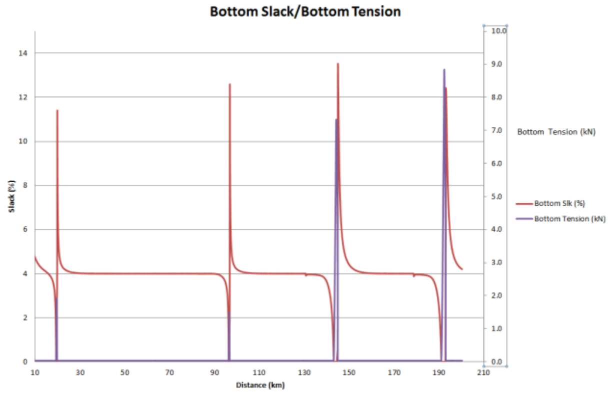

Figure 4: Bottom slack and tension results for constant water depth deployment

Whilst in each case the catenary and bottom slack was naturally affected it is evident that the titanium repeater has less impact with lower bottom tension being imparted.

The typical cable catenary representations from the simulation for both a titanium repeater and a steel repeater of similar geometry are shown in figures 5 and 6.

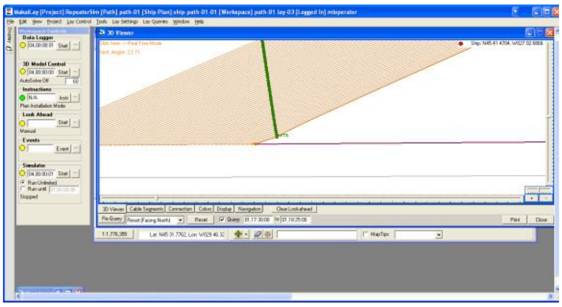

Figure 5: Cable catenary representation for a titanium repeater

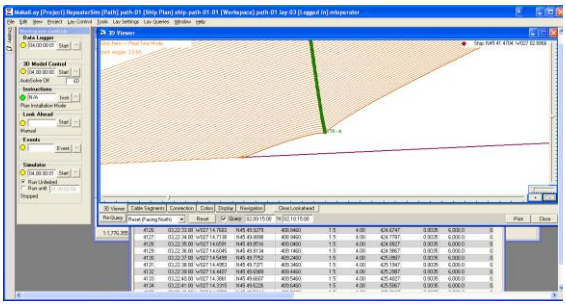

Figure 6: Cable catenary representation for a steel repeater

Deployment with 10° down slope bottom profile

A route profile was designed with a 10° down slope. Initially this was designed with a constant profile but then changed so that the down slope and deployment depth of the repeater was the same for each unit as shown in figure 7. This slope configuration is extreme and rarely encountered but has been included in order to show the level of control achievable in such harsh conditions with a light weight repeater.

In this test the 5 repeaters landed on the 10° down slope section of the route profile. To allow the bottom slack to remain at the required value of 3% down slope the vessel needed to increase the pay-out whilst the cable was being laid.

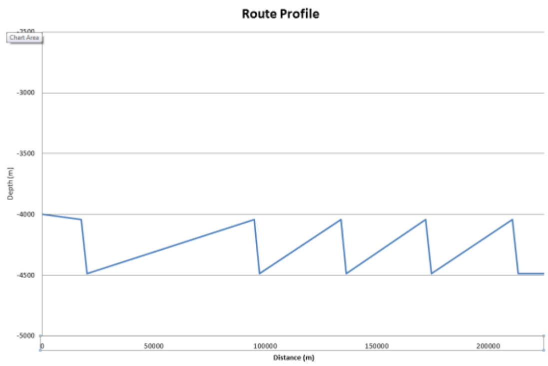

Figure 7: 10° down slope bottom profile

It is well known that the repeater in the catenary affects the slack transmission from vessel to seabed. In figure 8 a similar signature for the repeater touchdown has occurred however the magnitude of the tension and subsequent surplus of slack after touchdown has increased. Here again the titanium repeater has much less effect in terms of magnitude and time of disruption to the lay condition which provides significant control benefits for the marine installer.

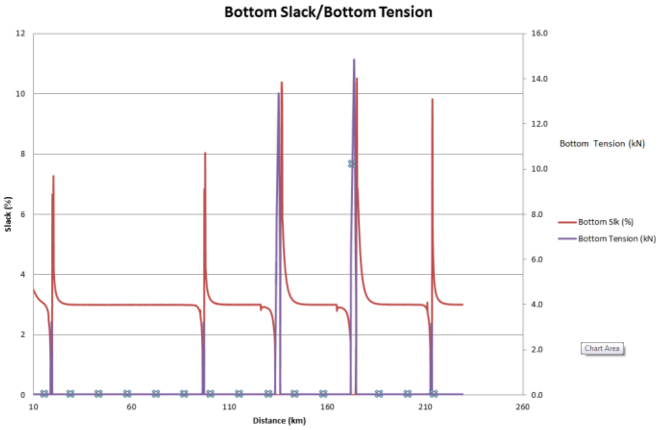

Figure 8: Bottom slack and tension results for 10° down slope bottom profile

Figures 9 and 10 show the typical Makai simulation of the cable catenary for both the titanium repeater and a typical BeCu housing for comparison

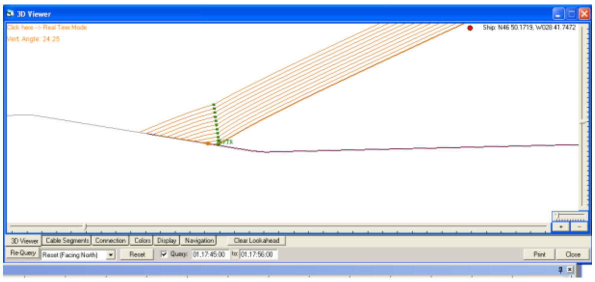

Figure 9: Cable catenary representation for a titanium repeater for 10° down slope bottom profile

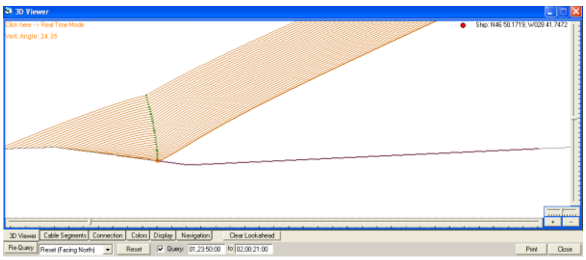

Figure 10: Cable catenary representation for BeCu repeater housing for 10° down slope bottom profile

4. CABLE INTERCONNECTIVITY AND INTEGRATION

The adoption of universal jointing technology as the primary cable integration methodology releases the repeater from the need to be factory integrated. Such flexibility allows the interfacing of repeaters with the system cable to be undertaken at any site of convenience, either shipboard, quayside or at the point of cable manufacture and to almost any cable type. Hand in hand with this approach it has been possible to streamline the integration process resulting in reduced opportunity for human error, improved process ergonomics and material flow and a reduction in jointing time. This has primarily been achieved by the introduction of predisposed in line repeater integration packs which remove the need for the operator to order and orientate the jointing components on the cable.

By adopting the mantra of "taking the jig to the cable rather that the cable to the jig" new semi-automated jointing equipment and multiple operation fixtures can now be brought to the cable centreline, rather than the multiple manual activity of previous jointing methods. Additional fresh thinking has been brought to bear on aspects of armour pressing, insulation re-instatement moulding and digital x-ray all of which strengthen a streamlined quality based wet plant integration process and methodology. An example of such an integration solution is shown in Figure 11 to 14.

Figure 11. Cable integration packs and new in line armour press being used on a titanium branching unit

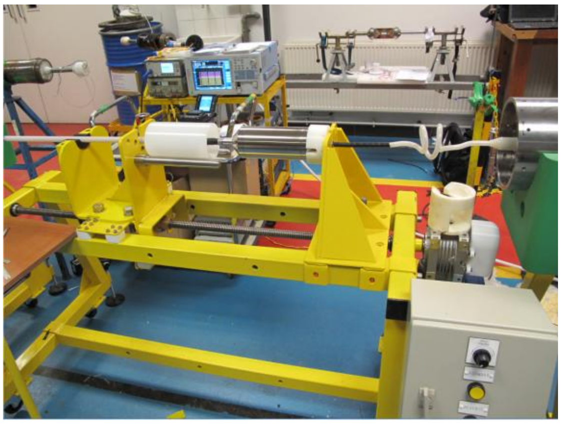

Figure 12. Multi-function jointing frame

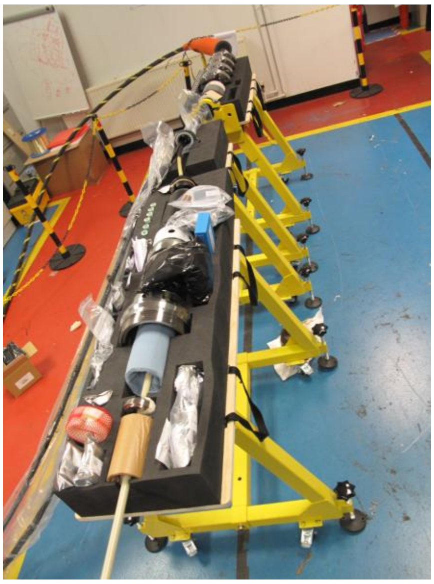

Figure 13. Integration pack layout

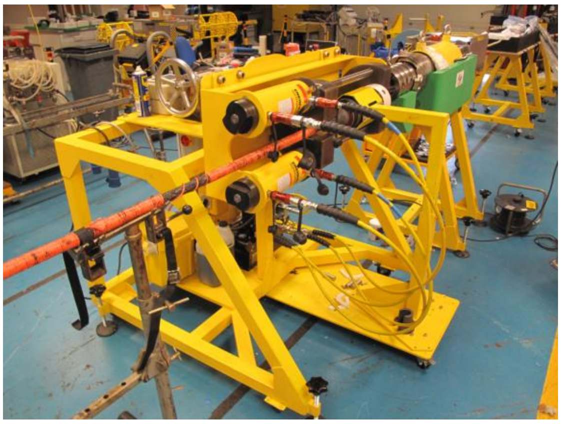

Figure 14. In-line armour press in action

5. HERMETIC SEALING

Hermetic sealing of a repeater usually occurs at three major interfaces, these being the housing to bulkhead, bulkhead to feed through and feed through to fibre levels.

Sealing to fibre

Hermetic sealing to fibre at levels of $\leq 1x10^{-9}$ cc/s (Helium) has in the main been achieved using glass to metal sealing or the use of epoxy seals, the latter being more of a calibrated leak which is highly dependent on the permeation and diffusion properties of the materials used along with the length of the leak path. Metallising whilst effective and well established requires complicated processing and can be problematical with variable yield for high fibre count seals within small geometries. This combined with the pressures of moving towards lead free solder to meet RoSH compliance has led connector and package designers to look at emerging technologies used in the packaging industry for subsea application. Such a solution is solder glass or “glass to glass” sealing which is rapidly being adopted by the oil and gas industry. Working together with industry it has been possible to develop a very small form factor, mechanically demountable, high fibre count sealing solution which meets the demanding requirements of space efficient subsea repeater applications. Typically a 16 fibre feed-through as shown in figure 15 can provide hermetic sealing to better than $1x10^{-9}$ cc/s whilst maintaining the capability to prevent water ingress at pressures up to 100 MPa In order to achieve this level of performance the feed-throughs have been qualified to industry and military accepted optical component test standards as well as industry specific operational requirements.

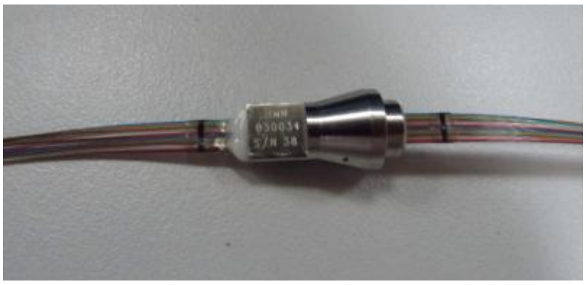

Figure 15: A typical high fibre count glass to glass seal

End closure and feed-through sealing

Traditional sealing methods for the bulkhead to sea case closure and feed-through to bulkhead are usually manufacturer specific solutions which include welding, soft metal gaskets and shear seals such as lead and copper. Whilst welding provides a significant level of sealing confidence it requires significant process control to avoid weld skip and prevents a demountable bulkhead solution for rework should this be required. Shear and plane gasket seals do offer a demountable bulkhead solution but suffer from difficulty in maintaining pre-load once recovered from deep water in say a typical repair scenario as constant force is required to maintain the sealing load, which is often lost once hydrostatic pressure has induced further creep and flow in the gasket material. Commerically available seals have been on the market for many years but have until now been overlooked due to unfounded fears of reliability. By adopting a fresh approach and adapting seals designed for aerospace application and combining them with a coating of a suitably compliant soft metal, it is possible to acheive hermeticity levels below $1x10^{-9}$ cc/s (He) whilst under full hydrostatic loads up to 83 MPa on the bulkhead, and maintain this level of sealing during recovery and re-deployment to 8,000m.

Figure 16: demountable bulkhead sealing system

Hydrogen managed terminations

The need for sealing against hydrogen ingress is well known and much engineering focus is brought to bear on the major sealing interfaces on the main housing but little is considered of the terminations themselves. By adopting a hydrogen managed approach to the cable coupling an additional level of protection can be provided especially where high levels of H_2 may be being generated through electrolysis, such as the return electrode on a branching unit if it is positioned in close proximity to the main housing or cable termination structure. Such an approach allows the ability to control levels of H_2 within the termination and thus restricts axial permeation along the cable and provides a secondary level of sealing for the repeater feed-through/termination interface. By adopting such an approach to cable interfacing it is possible to ensure higher levels of protection against H_2 ingress whilst still retaining full flexibility of integration with any universal joint qualified cable.

6. ADVANCEMENTS IN THERMAL MANAGEMENT

It is true to say that titanium does not provide any favours when comparing its thermal conductivty with competitor materials, sitting some 4 times lower than say BeCu. However thermal gradient through the repeater to sea is not just driven by the sea case material alone. In many instances where repeater and BU electronics are electrically isolated internally to the pressure sleeve it is the influence of the insulation sleeve or liner material and the management of the air gaps between the corresponding interfaces that have greater effect on the temperature. The selection of insulation material is as important as that for cable sheathing and termination moulding. In the majority of cases low or high density polyethylene is chosen as the statistical data set for high voltage reliability for this material spans many years and in a risk averse industry such as subsea telecoms there is much reluctance to change. However developments in computer and related micro electronics has driven the development of super dielectric materials that offer significant thermal transfer properties over traditional insulation polymers. The use of loaded Polyphenylene sulphide PPS and Linear crystal Polymer LCP has shown that thermal conductivity values some 30 times that of LDPE is possible without loss of dielectric strength. Using such materials it has been demonstrated that when driving amplifiers across the gain range of 16 to 24 dBm at drive currents of 0.6A to 1.2A, whilst the repeater is in water at 4°C to 35°C the thermal gradient across the repeater composite structure can be reduced to as low as 3.5°C. The challenges faced with using these materials are one of processing them into the form and size of product needed to suit the repeater or BU structure, and once formed establishing reliability through suitable in factory screening and accelerated age testing.

7. CONCLUSION

It is clear that by careful and inspired material selection it is possible to deliver innovative repeater and branching unit designs that push the mechanical design envelope. The use of titanium and the adoption of new emerging material technologies, provide significant improvements in marine handling, hermetic sealing and thermal management. Such material changes can be made without compromise to the strength to weight performance of the mechanical protection, and opens up opportunities for more streamlined integration, which resets the industry benchmark delivering new and attractive opportunities to the market.

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