A NEW ITERATION IN THE DESIGN OF SUBMARINE CABLES

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Abstract: Client demands for cables with higher capacity and longer spans have resulted in a revision of the requirements for submarine cables. This has created an opportunity for a new iteration in the submarine cable design structure. This paper will review the history of transoceanic optical fibre cable design parameters and where the standard commercial submarine cables offered to clients are positioned today. The requirements of the next design iteration of submarine cables are discussed and the design solutions presented. Increased fibre counts, which result in more subsea amplifiers and increased energy requirements, also require the optimization of the cable conductor resistance for long haul transmission routes. This paper describes the cable designs and manufacturing processes which optimize the structure of loose tube cables to increase fibre counts and decrease the conductor resistance, while meeting client requirements for deployment and recovery under adverse weather conditions in 8000m water depth.

1. INTRODUCTION

Today, repeatered submarine cables are employed on long systems (more than 500~600km), where it is necessary to power feed submerged equipment for optical amplification and deploy in water depths down to 8000m. Submarine cables must be capable of recovery from the seabed for repair, even in severe weather conditions, without any impairment to their transmission performance or reliability.

2. HISTORICAL TRENDS IN CABLE DESIGN

It is often useful to look back at the track record of submarine cable systems which are in service and in order to identify what trends and features can be observed. The dataset used for this exercise covers 278 in-service & planned cables obtained from the STF Cable Almanac [1]. Figure 1 reveals the length of cable systems by published RFS (Ready for service) year. The cumulative data curve shows that there was currently over 1.14 million kilometers (kms) of cable in service at the end of 2018 and this is forecast to increase by over 252,000 kms at the end 2020 to approximately 1.4 million kms of cable.

This curve reveals that the expected length of cable to come into service in 2020 is over 179,000 kms.

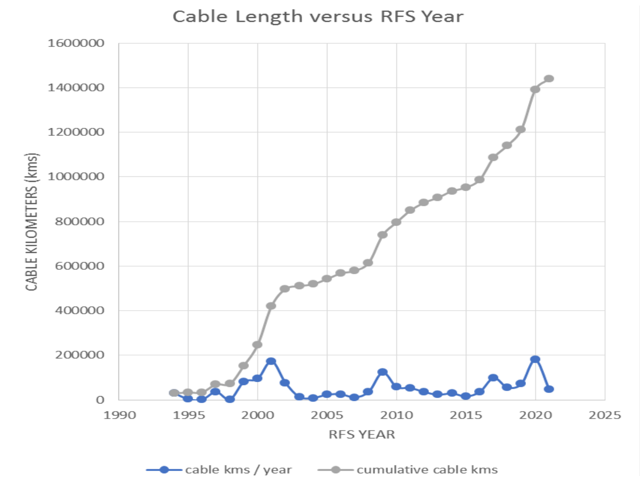

Figure 1: Cable Length in Service by RFS Year (25 years of data)

It is interesting to look at the average lengths of cable system (and number of systems) produced each year to identify any trends (Figures 2 & 3). It can be seen that the average length of cable systems appears to be on an upward trend over the period 2005 to 2020.

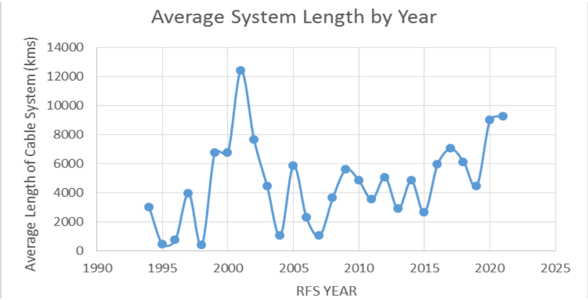

Figure 2: Average System Length by RFS Year

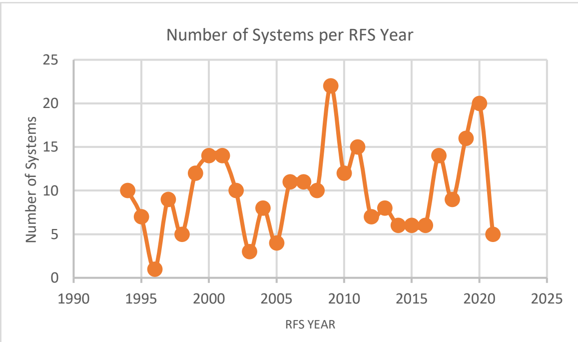

Figure 3: Number of Systems per RFS Year

It is expected that 20 new cable systems will be RFS in 2020, the highest number for over 10 years. The average number of fibers in cable systems by RFS year is presented in Figure 4 below.

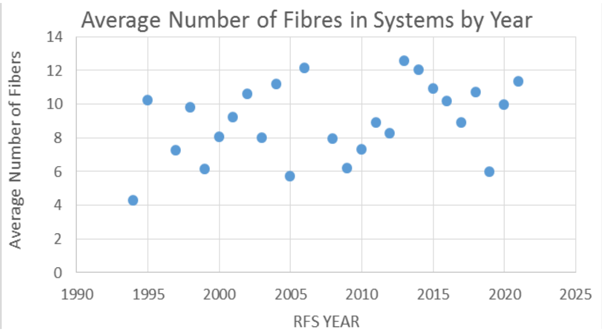

Figure 4: Average Number of Fibres in Cable Systems by RFS Year

This data is interesting in that the average number of fibers in cables generally tends to vary from 6 to 12 (3 fiber pairs to 6 fiber pairs) and there has not been any definitive evidence of increases in the fiber counts of cables to date (Figure 5).

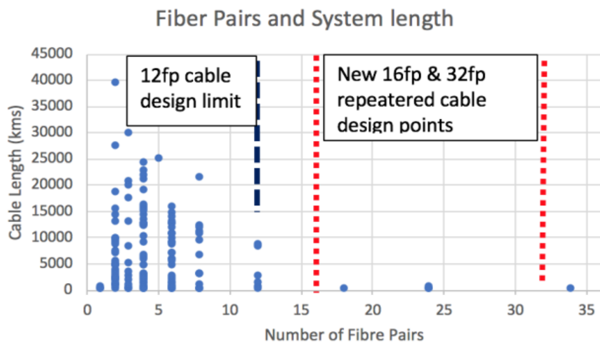

Figure 5: Cable System Length Versus Number of Fibre Pairs

The longest system networks tend to have 2, 3 or 4 fiber pairs, while the maximum number of fiber pairs used in repeatered systems has been 12 to date. Higher counts of fiber pairs are for much shorter un-repeatered cable systems. Therefore, the current requests from clients to incorporate 16 fiber pairs or even 32 fiber pairs into a repeatered cable system moves repeatered cable design & manufacture into unexplored territory.

3. REQUIREMENTS FROM NEW CLIENTS

Based on long haul system, and explosion of data demand, driven by new clients' requirement, repeatered cables will have new requirements. Some of these requirements are discussed here.

- Increased fiber count

As we have seen from Figure 5, to date the maximum number of fiber pairs used in repeatered cable system has been 12. To boost transmission capacity requests for cable designs utilizing 16 or even 32 fiber pairs have been proposed by clients for future repeatered systems.

- New large effective area fiber

Long haul systems require low attenuation characteristics and improved expansion capacity for future upgrades in transmission technology. The benefits offered by the larger effective area, G654D fibers have recently been specified by clients for new systems to meet these requirements.

- Low conductor resistance

To allow longer systems to be built and to account for the increased number of subsea amplifiers housed in repeaters (with increased power requirements), it is necessary to consider the power drop along cable.

- High voltage

Due to the increased number of amplifiers housed in repeaters (and with the increased power requirements) system design voltage is increasing from 10kV to 15kV.

4. CABLE DESIGN

4.1 General Requirements

The cable has the primary objective to protect the fibers from the external forces and to provide a means to connect data centers through the wet-plant equipment. The cable also has to transmit power to the submerged equipment. The protection of the optical fibers and the power conductor properties have to be stable not only for the 25-year design life during normal operations but also during the phases of manufacturing, deployment, and if required during any recovery and repair of the system.

ITEM	SPECIFICATION
Water Depth	8000m
System Voltage	15kV
Optical Attenuation	<0.16dB/km
Number of fiber pairs	16 or 32
Conductor Resistance	Approx. 0.7 ohm/km

Table 1: Cable Characteristics

4.1.1 Pressure and Temperature Range

The cable has to support the water pressure at the maximum depth where it is installed without collapsing. At the 8000m maximum depth of a typical deep-sea cable, the pressure is 80MPa.

For the qualification of new submarine cables the operational temperature ranges expected to be achieved are between -10℃ and +40℃. Cable storage and transportation requirements have to meet a wider range of -30℃ to +60℃ without any impairment to the cable's performance.

4.1.2 Water and Gaseous Ingress

Submarine cables have to resist water ingress at depths down to 8000m or more in the case of a complete cable break on the seabed.

Another major concern to submarine cables is the possible increase in attenuation in the operating transmission window of optical fibers due to the chemical reaction of the fibers' silica-based core material with hydrogen gas. It is now even more important to limit these effects because of the stringent broadband, gain slope management requirements for DWDM systems since the effect is not constant in the entire transmission window.

4.1.3 Manufacturing and Installation Requirements

The cable, cable joints, and terminations need to withstand laying, burial, recovery, possible reuse, and normal cable ship handling without degradation of mechanical or optical properties.

4.2 Cable Structure

A LW deep water submarine cable, normally has six basic elements:

- The optical fiber
- The fiber gel
- The optical package
- Inner strength member
- Conductor element
- Insulation

4.2.1 The optical package

According to the fiber type, and fiber quantity, and based on the slack length, it is possible to calculate the Fibre In Metal Tube (FIMT) inner diameter.

G652D		
Fiber OD	Bend Radius	Space Ratio
250um	50mm	0.3
G654D		
Fiber OD	Bend Radius	Slack Length
270um	200mm	1.2‰

Table 2: Fiber / Tube Characteristics

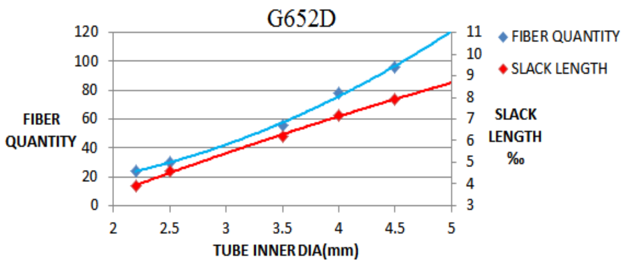

Figure 6: Fiber Quantity and Slack Length

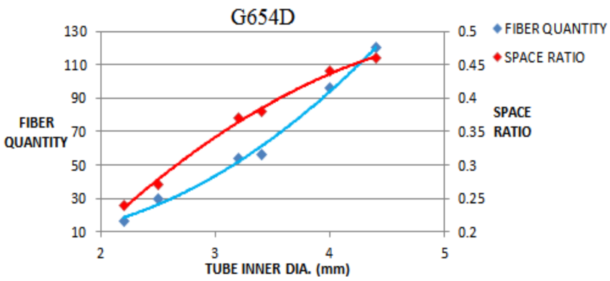

Figure 7: Fiber Quantity and Space Ratio

In Figure 6 the Slack Length has been defined as :

(Fiber Length - Tube Length) / Tube length

While in Figure 7 the Space Ratio has been defined as :

Fiber Area * Fiber Quantity / Tube Inner Area

The data points indicated on the above design curves covering tube dimensions and fiber quantities have been confirmed to achieve low loss cabling effects by manufacturing R&D and system lengths of cable.

4.2.2 Inner Structure

There are several alternative designs of composite conductor: the Warrington Vault, semi-torsionally balanced structures, and the C-section shell.

Some popular designs have been based on a Warrington Vault, and using existing production equipment wire bobbin layout new designs can utilize strength member designs using multiples of 4 wire arrangements. Here we examine inner steel wire design structure utilizing 3 wire diameters for production efficiency. Designs based on 1 wire diameter (one layer), 2 wire diameters (two layer, same wires' quantity) and 3 wire diameters (two layer, same wires' quantity) are discussed in this paper.

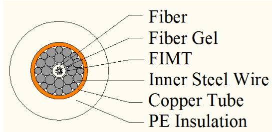

Figure 8: Typical Structure of Warrington Vault

The diameter of the central tube dictates the diameter and potentially number of inner armour wires used in the cable design. From Figure 9 it is seen the effect tube diameter has on wire diameter and the LW cable CBL (Cable Breaking Load) based on the various wire diameters selected from the Warrington Vault design.

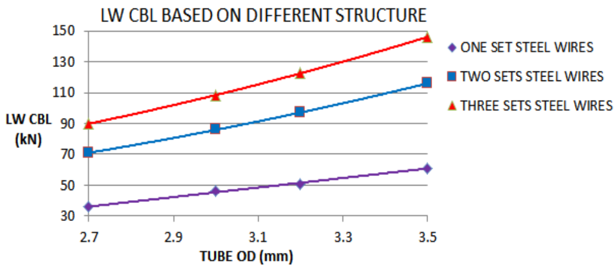

Figure 9: LW Cable CBL

Figure 9 shows the design curves relating LW cable Break Load (CBL) for a range of tube diameters, based on 1, 2 & 3 sets of wire diameters, making up the Warrington Vault structure. Taking the 3.2 diameter tube for discussion, the cable tensile breaking load can be adjusted from 51kN to 123kN by adjusting the number and grade wires.

4.2.3 Composite Conductor Element

For long haul Repeater telecommunication systems, the composite conductor (formed of steel wires and metallic conductor tube) has to be designed for low conductor resistance.

Traditionally a copper tube has been utilized to surround the steel wires in LW cable. However, it is also interesting to examine the benefits offered by using an aluminium tube conductor.

The use of Aluminium in submarine optical cable designs has been treated cautiously due to the reactivity of aluminium and the potential for galvanic corrosion when the aluminium & steel react in the presence of salt water. The relative positions and galvanic potential of these cable metals are summarised below (most cathodic at the top, most anodic at the bottom) :

Copper has a potential of -0.30 to -0.36V
Steel has a potential of -0.61 to -0.70V
Aluminium & alloys have a potential of -0.79 to -1.0V

As aluminium & its alloys are more anodic than either steel or copper, the corrosion mechanisms in LW cable will be different, potentially leading to hydrogen generation.

Anecdotal evidence from deep water repairs on LWP cables using an aluminium screen have revealed the presence of hydrogen, which was observed to burn freely from the cut cable end for several tens of minutes.

Several different solutions are introduced here based on a LW cable design with ø3.2mm tube and a (8+8+8) wire Warrington Vault, using these two conductor metals:

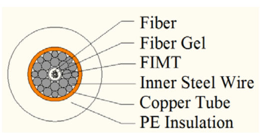

Figure 10: Thick Copper Tube

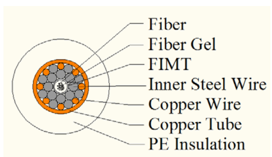

Figure 11: Copper Wire & Tube

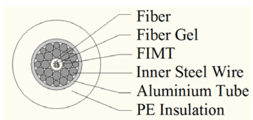

Figure 12: Aluminium Tube

Repeater System Cable (ø3.2mm tube) with copper, based on Warrington Vault	
Design Structure	Resistance
Steel wires, and 0.4mm copper layer	1.02Ω/km
Steel wires, and 0.6mm copper layer	0.74Ω/km
One set copper wires, and 0.4mm copper layer	0.61Ω/km
One set copper wire, and 0.6mm copper layer	0.50Ω/km

Table 3: Resistance Based on Copper Structures

Table 3 demonstrates that the cable composite conductor resistance can be lowered by increasing the area of copper using in the design. The copper content can be increased by using thicker tubes or by changing some of the steel wires for copper wires. Similar changes can also be obtained when using an aluminium conductor as shown in Table 4.

Repeater System Cable (ø3.2mm tube) with Aluminium, based on Warrington Vault	
Design Structure	Resistance
Steel wires, and 0.4mm aluminium layer	1.38 Ω/km
Steel wires, and 0.6mm aluminium layer	1.11 Ω/km
Steel wires, and 0.68mm aluminium layer	1.02 Ω/km
Steel wires, and 1.0mm aluminium layer	0.74 Ω/km

Table 4: Resistance Based on Aluminium Structures

Choosing the 0.74 Ω/km cable design for comparison and discussion, Table 5 reveals some of the key differentiators between the copper and aluminium based composite conductor LW cables.

The Hydrodynamic constant, H (Rad.m/s) is defined as :

$$H = \sqrt{2w/C_D \rho d}$$

W: the cable weight in water, (N/m)

ρ: the seawater density, (1060kg/m³)

d: the cable diameter, (m)

CD: the drag coefficient, (2.2 for lay)

and the Cable Breaking Load, CBL (kN) has been conservatively calculated based on material specifications at minimum limits and tolerances.

	COPPER			ALUMINUM		
Resistance	0.74Ω					
PE Thickness	Same Thickness					
	One Set	Two Sets	Three Sets	One Set	Two Sets	Three Sets
Conductor Thickness (mm)	0.92	0.65	0.6	1.44	1.05	1
Cable OD (mm)	18.32	20.6	20.54	19.34	21.36	21.3
Weight In Water (kg/km)	339	457	546	233	361	455
H (rad.m/s)	0.4	0.44	0.48	0.32	0.38	0.43
CBL (Calcualted, kN)	51	97	123	51	97	123
Approx. Cost Reduction	1	0.88	0.89	0.58	0.6	0.62

Table 5 : Summary of 1, 2 & 3 Wire Designs with Copper & Aluminium Conductors (0.74 Ω/km)

Note: based on aluminium cost being 55% of the copper cost and ignoring fiber costs.

Based on different structure and different conductor material (copper and aluminium), FEA analysis has been introduced to compare the advantage and disadvantage.

Tensile and compress simulation have been completed based on ø3.2mm tube OD, with the copper and aluminium conductors.

Take the 10kN tensile force 5kN/100mm compression force for example. Simulation is ignoring the PE insulation layer, water block gel, fiber and fiber jelly.

Force Applied	Structure (Thickness of Aluminum)	Aluminum: Deformation of whole cable(mm)	Aluminum: Strain of whole cable	Aluminum: Stress of FIMT(MPa)
Compression 5kN/100mm	*Three sets wires (1.0mm)*	0.00034942	8.85536E-05	12.551
	Three sets wires (0.6mm)	0.00072243	0.00016015	20.822
	Two sets wires (1.0mm)	0.00057416	0.00010945	16.874
	One set wires (1.0mm)	0.00058612	0.00016641	19.924

Table 6 : Summary Results of Aluminium Conductor

Force Applied	Structure	Copper (0.6mm Thickness): Deformation of whole cable(mm)	Copper (0.6mm Thickness): Strain of whole cable	Copper (0.6mm Thickness): Stress of FIMT(MPa)
Compression 5kN/100mm	*Three sets wires*	0.00066156	0.00015273	19.908
	Two sets wires	0.00098366	0.00019989	25.818
	One set wires	0.0011169	0.00030989	35.445
Tensile 10kN	*Three sets wires*	0.13116	0.0012484	154.88
	Two sets wires	0.16069	0.001605	195.79
	One set wires	0.27226	0.0022373	335.79

Table 7 : Summary Results of Copper Conductor

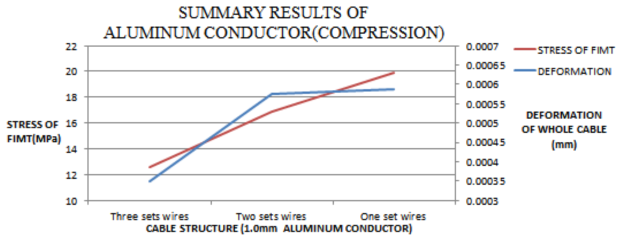

Figure 13: Summary Compression Results of Aluminium Conductor (1.0mm)

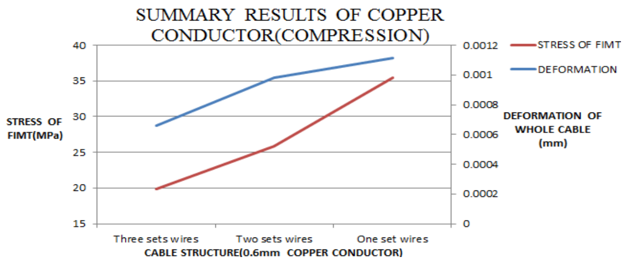

Figure 14: Summary Compression Results of Copper Conductor (0.6mm)

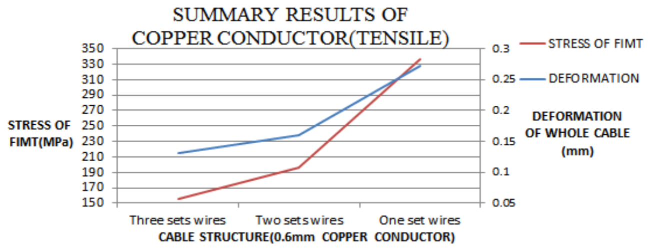

Figure 15: Summary Tensile Results of Copper Conductor (0.6mm)

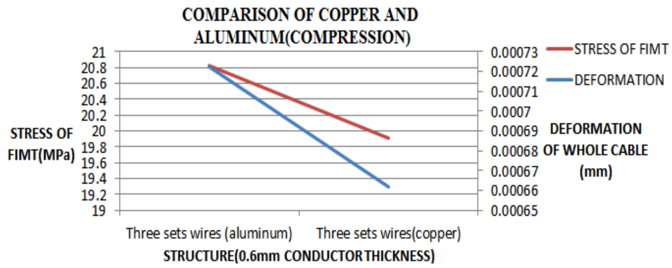

Figure 16: Comparison of Compression Results Between Copper and Aluminium

From the results shown in Tables 6 and 7, the designs using 3 diameters of wire (8+8+8) are more robust in deformation and offer better protection of FIMT.

Based on the 0.74Ω/km cable design variants, the 1.0mm thickness aluminium conductor design is equivalent to 0.6mm thickness copper conductor. However, from the calculations above, the thicker aluminium conductor offers better mechanical capacity than copper. When the conductor thickness is same for both materials, the aluminium does not offer the same crush resistance as the copper. Some simulation photos as below:

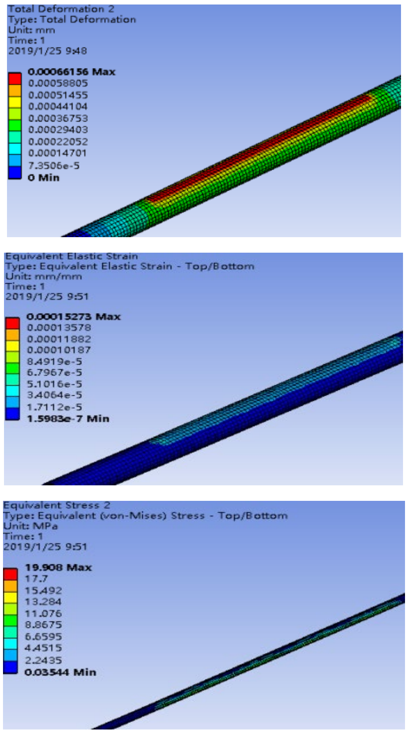

Figure 17: Simulation Results for Three Sets Wires Using 0.6mm Copper Conductor (Compression)

5. CABLE SEA BOTTOM STABILITY

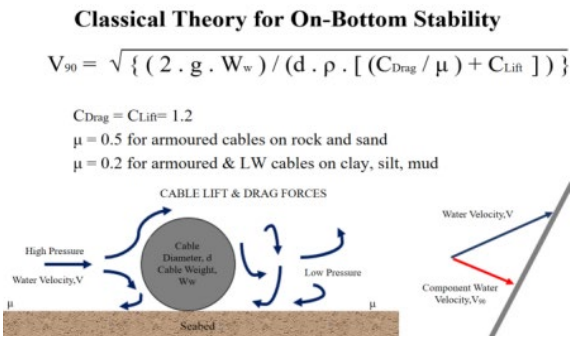

Figure 18: Classical Theory for On Bottom Stability

Using the cable data in Table 5 the on-bottom stability of the copper and aluminium based composite conductor LW cables can be calculated.

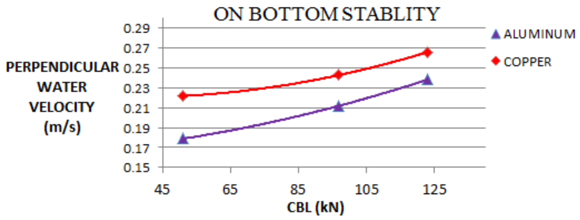

Figure 19: LW Cable Bottom Stability

All the aluminium composite conductor designs are more susceptible to displacement by water currents than the corresponding copper composite conductor designs.

The aluminium composite conductor with 1 wire diameter can be moved by currents 20% lower than the corresponding copper variant. The 2 sets of wire aluminium composite conductor design can be moved by currents 13% lower, while the 3 sets of wires Warrington Vault design with aluminium composite conductor can be moved by currents 10% lower than the copper equivalent.

This would imply that the LW cables with an aluminium conductor could be more sensitive to abrasion damage.

6. CABLE HYDRODYNAMIC CONSTANT

The variation in hydrodynamic constant for the cable deployment is shown in Figure 21 and the affect this has on the cable lay angle is shown in Figure 22.

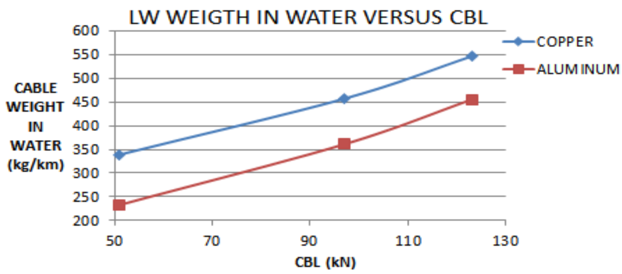

Figure 20: LW Weight in Water

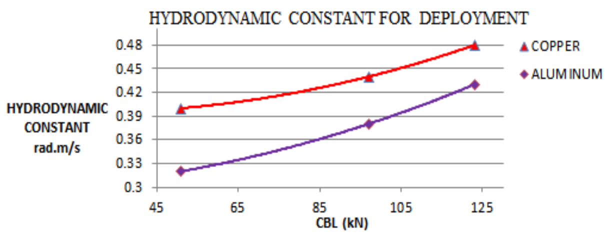

Figure 21: Hydrodynamic Constant for Deployment

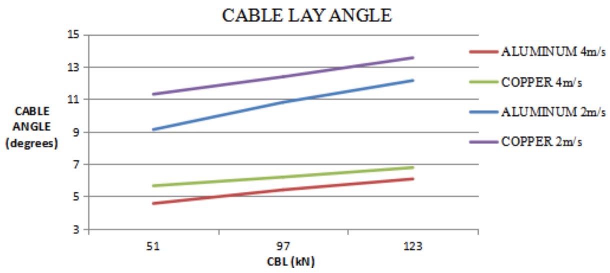

Figure 22: Cable Lay Angle(degree)

7. CABLE DEPLOYMENT & RECOVERY

LW cable designs using an Aluminium conductor have been shown to have a lower Hydrodynamic constant in Table 5. The variation of Hydrodynamic constant is presented in Figure 21 and the corresponding cable lay angle in Figure 22. These curves show that the deployment angles for both conductors at practical speeds fall within similar ranges being within 2 degrees of each other.

When considering cable recovery tensions, it is normal to consider cable recovery under adverse conditions (75-degree cable lead, 3m/s vertical sheave velocity and a speed of 0.2 knots, see Figure 23).

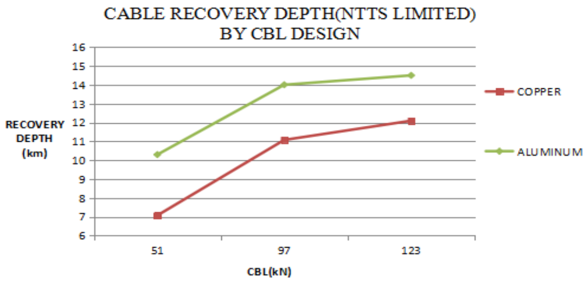

Figure 23: Cable Recovery Depth

The cable recovery depth shows that the aluminium composite conductor designs can be recovered from water depths approximately 2km deeper than the similar designs using copper.

When the recovery operation is analysed with larger repeater housing in the water column, the maximum water depths for recovery under adverse conditions reduce.

Figure 24 shows the maximum water depths for the cable designs. Both the Aluminium and copper composite conductor designs based on three sets wires Warrington Vault can be recovered from more than 8000m water depth. However, only the aluminium composite conductor using one set wires can be recovered from 8000m. Calculations have assumed a repeater weight in water of 250kgs.

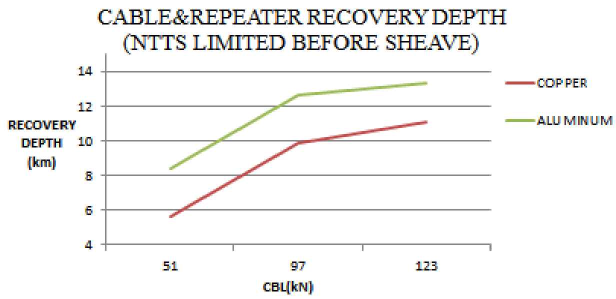

Figure 24: Cable & Repeater Recovery Depth (NTTS Limited Before Sheave)

Common to both the copper and aluminium conductor LW cable designs, during the recovery of a repeater around the cable-ship sheave the inboard tension has to increase higher than the outboard tension due to the magnification lever effect of the rigid housing on the sheave. [2] To cope with a range of repeater rigid lengths and diameters it is proposed that an additional layer of reinforcement is applied over the LW or LWP cable for a distance of approximately 80m to allow recovery of the repeater around the sheave at the higher peak inboard tensions. The reinforcement could be a Kevlar braid or similar, which would not add significant additional cable weight to the recovery operation.

8. DISCUSSION

It has been the traditional approach amongst submarine cable system suppliers to design a family of cables based on the deep-sea LW cable as the core cable element for all cable types.

This approach may simplify the cable tracking & management of cables during production, but surely the use of a cable core qualified for use in 8000m water depth, is not economically desirable in say a regional cable system where most of the cables are armoured and deployed in less than 3000m water depth.

With new high fibre count cable structures it could be possible to reduce the strength and costs of the core cable to be used in shallow water armoured cables by reducing the steel wire content (from a 3 wire diameter (three sets) Warrington Vault to a single layer of (one set) wires) while maintaining the required low conductor resistance.

The influence of the larger weight and physical size of repeaters with higher amplifier counts on cable recovery also have to be considered. Common to both the copper and aluminium LW cable designs, it does not make engineering sense to design a deep water LW cable which is capable of recovering inline repeaters from the maximum design depth of 8000m under adverse weather conditions, while considering any inboard tension increases due to magnification effects as the repeater passes over the ship sheave as is the current practice. A new methodology is proposed whereby the LW cable is capable of recovering only the cable from the maximum design depth under adverse weather conditions with a small contingency to cover additional current drag and repeater housing weight & drag.

A minor change to the LW cable on either side of the repeater housing is proposed using a short length of light reinforcement which can be applied to deep sea repeaters. This reinforcement would support the increased cable tension as the longer repeater housing pivots on the ship sheave with corresponding inboard cable tension magnification effect.

Such a methodology would generate significate cost savings for every kilometre of cable manufactured as repeaters deployed in 7000 to 8000m water depth are rare, and route planning can often avoid system deployments in these depths.

9. CONCLUSION

The use of an aluminium composite conductor appears an attractive option to achieve the required cable characteristics for 16fp repeatered cable, while maintaining sufficient strength to allow recovery in adverse weather conditions from beyond 8000m.

However, the lighter aluminium composite conductor designs are more sensitive to movement on the sea bottom due to currents which could result in more abrasion related issues.

The long-term corrosion of the aluminium / steel material combination has still to be evaluated and the effects of hydrogen generation to be fully investigated.

10. REFERENCES

[1] Submarine Telecoms Forum, Submarine Cable Almanac online version, Issue 28, November 2018. (https://subtelforum.com/products/submarine-cable-almanac/)

[2] Jerry Brown, "Hengtong Marine, Connecting the world, connecting the future". Submarine Telecoms Forum Magazine #103 Data Centers and New Technology, pages 51 -54.

