ALUMINIUM CONDUCTOR IN SUBMARINE CABLES, A COST/PERFORMANCE OPTIMIZED SOLUTION

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Abstract: One of the most expensive raw materials used in current repeatered submarine cables is the copper conductor enabling the powering of the submerged equipment, such as repeaters and branching units. The cost of the conductor is particularly significant for long haul systems requiring very low electrical resistivity to comply with single-end feed powering requirement: the copper section has to be increased to reduce the resistivity value. As a result, one clear axis to optimize the submarine cable cost is to replace the copper conductor by another, cheaper material. The aluminium conductor provides several benefits and advantages compared to copper, including:

- A better cost-effectiveness, while maintaining a performance equal to copper;
- A more stable supply market, which has benefited over the past fifteen years from technology improvements, mainly driven by the oil & gas industry. This has led to the development of new industrial techniques and equipment now available for aluminium processing and welding on long distances;
- A potential for higher speed of production to speed-up the delivery of new systems;
- An enabler to achieve solutions for low direct current resistance (DCR) with higher number of fibre pairs.

As a submarine transmission systems supplier, our cable supplier company have developed and qualified a new variant of cable based on an aluminium conductor. This paper presents the aluminium conductor cable features and the testing and qualification programmes undertaken to demonstrate its suitability for ultra-long-haul transmission systems. It includes results of mechanical, electrical, optical and environmental tests performed on deep sea and armoured cables. It also describes the testing of associated jointing equipment to validate the compatibility of the aluminium conductor cable with joints. Finally, the results of a specific sea trial with this cable variant are presented.
The paper also presents other fields of applications where aluminium conductor submarine cable proves to be a cost-effective solution.

1. INTRODUCTION

Copper is one of the most expensive raw materials in traditional optical submarine cables: it ensures the powering of the submerged plant.

The higher the power feeding needs are, the lower the resistivity of the cable must be, and the higher the copper section in submarine cable design needs to be.

To optimize submarine cable cost, one of the most effective solutions is to replace the copper raw material by a cheaper one: aluminium.

2. CABLE DESIGN AND FEATURES

Design work has been conducted on the basis of 17mm 1Ohm/km OALC-4 cable (reference [1]).

The first step of this design work consisted in the identification of the aluminium grade corresponding to submarine cable requirements.

This aluminium grade had to satisfy ohmic resistance specifications (guaranteed low value), have good welding properties and, additionally, have a reasonable price.

Once the aluminium grade had been defined, cable design was adapted, taking into account the aluminium specification limits. Aluminium layer thickness has been calculated so that the ohmic resistance value of the aluminium conductor cable is equal to copper conductor cable one (1 Ohm/km). In fact, the slightly higher resistivity value of aluminium compared to copper implies that the aluminium conductor is marginally thicker than copper.

However, the insulated cable outer diameter has been maintained at 17mm by slightly decreasing the polyethylene insulation layer. This reduced layer still complies very largely with the 15kV over the 25 years of the system lifetime. This point has been checked during qualification and characterization programs described in paragraph 3.

As the insulated cable outer diameter for copper and for aluminium is equal, all OALC-4 cable existing protection types (Light Weight Protected, Single Armour, Double Armour) are also fit for purpose for the aluminium conductor cable.

The OALC-4 aluminium conductor cable features are the same as OALC-4 copper conductor cable ones. The same mechanical, electrical and optical performances are reached with this new composite conductor raw material.

The associated cable joint design has also been adapted. The required changes were very small, only impacting the cable conductor anchorage, that was modified to fit with aluminium layer greater thickness.

The joint performance is also maintained at the same level as for copper conductor cable joints.

Universal jointing (UJ) product design adaptation required for aluminium conductor cable are also anticipated to remain marginal.

3. CABLE AND JOINT QUALIFICATION

A comprehensive qualification program has been performed, according to ITU-T-G.976 [2] and ASN standards, to demonstrate the robustness of the aluminium conductor cable.

This program included mechanical, electrical and optical testing. Optical fibres included in qualification cable prototype were chosen so that to cover the last fibre generations, including ultra large effective area (150µm^2), most bending sensitive fibres.

3.1. Mechanical qualification

As part of mechanical qualification, some of the tests were performed on cable samples, and other ones on cable and joint samples.

A stopper test was performed on Light Weight (LW) cable sample. The purpose of this test was to check the behaviour of cable during cable holding with stoppers, up to NTTS load, and with fatigue constraints up to NOTS load. Cable sample integrity was checked after test, and, more particularly that no slippage was found between the different cable layers.

A flexure resistance test was performed on LW cable sample. The purpose of this test was to check that the cable meets the bend requirements imposed by handling operations. The cable is alternatively bent (25 cycles, 50 bends) between two sheaves. The cable structure was checked after the test and no structure degradation was found. Resistance to pressure and electrical performance of the tested cable sample were also checked through hydrostatic pressure test at 1000 bars for 24 hours and high voltage test at 200kV for 1 hour respectively.

Figure 1: Flexure resistance test equipment

Crush tests have been performed on Light Weight (LW) but also Single Armour (SA) and Double Armour (DA) cable samples. The purpose of these tests was to prove that the cable can sustain the crush due to storage in cable tanks. Cable samples were maintained between two plates with crush loads for one hour. The applied loads were much higher than the load corresponding to weight of cable in a full tank. Cable samples were then submitted to hydrostatic pressure test (1000 bars 24 hours), high voltage test (200kV 1 hour) and cable examination. Results fully complied to requirements.

Figure 2: Crush test equipment

Impact tests have been performed on Light Weight (LW), Single Armour (SA) and Double Armour (DA) cable samples. The aim of these tests was to prove that the cable can sustain the impact it could be accidentally exposed to, during its storage in cable tanks or during handling. A weight was dropped vertically on cable samples. Applied energies were at least equivalent to those applied in copper conductor cable qualification. Cable samples were then submitted to hydrostatic pressure test (1000 bars 24 hours), high voltage test (200kV 1 hour) and cable examination. No electrical breakdown occurred, and no cable structure degradation was found after the test sequence.

Figure 3: Impact test equipment

Minimum storage diameter tests have been performed on LW cable samples. The purpose of this test was to check that cable storage on small diameter did not affect its performances. The cable samples have been wound on 1 m and 1.80 m diameters.

The samples were submitted to thermal cycles. Optical measurements after test did not reveal any attenuation variation higher than measurement accuracy.

Cable samples were then submitted to hydrostatic pressure test (1000 bars 24 hours), high voltage test (200kV 1 hour) and cable examination. No electrical breakdown occurred, and no cable structure degradation was found after the test sequence.

A water penetration test was performed on LW cable sample. The aim of the test was to prove that the water penetration inside cable structure was limited in time and in length in case of cable cut happens on sea bed. A 1km long sample was submitted to 500 bars water pressure for 14 days, following standard test protocol. Water penetration in the cable vault was measured after test. Again, all results were compliant with requirements, allowing to guarantee a propagation of less than 250m in shallow water (<1000m water depth) and less than 1000m in deep water (> 1000m water depth).

A mechanical test sequence was performed on cable and joint sample, including:

- Fixed gyration tensile test at NTTS,
- Fatigue test up to NOTS,
- Torsion test (+/-0.2 turn/m),
- Free gyration tensile test at NTTS,
- Reverse bend test (15 cycles / 30 passages on sheaves under low load)
- Sheave test at NTTS.

Once tested, the sample was submitted to examination test sequence, including:

- Joint external mechanical dissection,
- Hydrostatic pressure test (1000 bars for 24 hours),
- High voltage test (200kV 1 hour),
- Ohmic resistance test,
- Insulated joint dissection,
- Anchoring dissection of one of the anchoring, tensile test up to break (>90% of cable UTS) of the other one.

The full test sequence was compliant with requirements. No degradation of cable nor of cable joint was observed.

3.2. Electrical qualification

Electrical qualification tests were performed on LW cable samples and LW joints (on Jointing Boxes (JB) and Extremity Boxes (EB)).

Short-time and long-time high voltage tests were performed on LW cable sample, preliminarily submitted to flexure resistance test. The purpose of this test was to check that the cable electrical performances were compliant with 15kV for 25 years, even after bending stresses, representative of those imposed by handling operations. The cable was alternatively bent (25 cycles, 50 bends) between two sheaves. The cable sample was then submitted to hydrostatic pressure (1000 bars for 24 hours). The electrical performances of the sample were then assessed through short-time high voltage test (200kV 1 hour) and long-time high voltage test (40kV for 3 months). No electrical breakdown occurred during both electrical tests.

Electrical qualification tests on jointing products were performed through a moulding process qualification. Two jointing products have been tested: Joint boxes and extremity boxes.

For each product, 8 joints have been assembled and moulded using minimum, nominal or maximum moulding temperatures. 2 additional joints have been moulded and remoulded.
All joints have then been submitted to X-Ray analysis, high voltage test (200kV 1 hour) and microtome test.

All results were compliant with requirements.

3.3. Optical qualification

In addition to mechanical and electrical qualifications, some tests were dedicated to the qualification of optical fibre behaviour inside aluminium conductor cable, simulating 25 years cable design life.

The first test was the cable ageing test. A 3km LW cable on drum was submitted to an accelerated ageing test at 70°C for 1800 hours (simulating 25 years at 3°C). Fibre attenuation variations were monitored during the test on all fibres contained in the cable prototype (16 fibres). No attenuation increase higher than measurement accuracy was measured during the test.

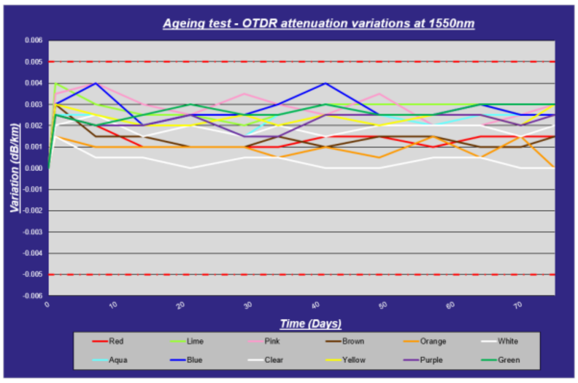

Figure 4: Optical follow-up at 1550nm during ageing test

The second test was an accelerated corrosion test performed on a DA cable, placed in a tank with salt water heated at 48°C for 18 months. 1km of DA cable containing one tube junction repair in the middle (to introduce a discontinuity of the hydrogen barrier provided by the cable tube) was immerged. No bitumen was put on armour wires and some areas of the armour wires were mechanically abraded to remove the galvanization, to maximize the corrosion effect. Attenuation variations at 1240nm and 1550nm have been measured during the test. No variations greater than measurement accuracy were measured.

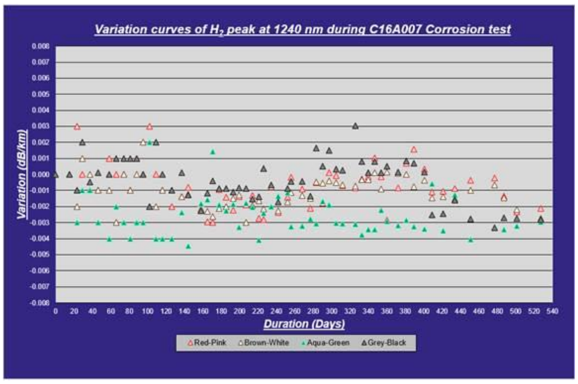

Figure 5: Optical follow-up at 1240nm during corrosion test

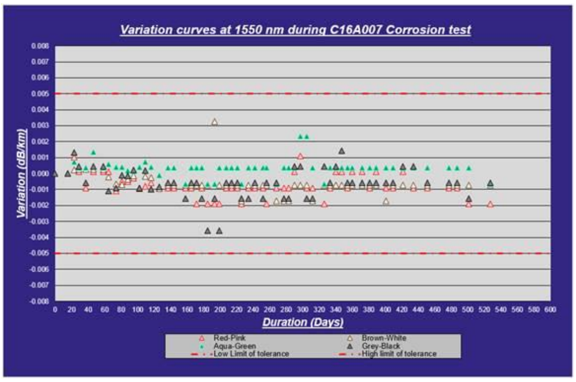

Figure 6: Optical follow-up at 1550nm during corrosion test

4. CABLE AND JOINT CHARACTERIZATION

In addition to previously described qualification tests performed according to ITU and completed by ASN standards (some under more severe conditions), additional specific characterization tests have been performed to further evaluate the aluminium conductor cable performance.

4.1. Electrical characterization

As part of the electrical characterization, a statistical study has been performed to better assess the performance margin of aluminium conductor cable versus 15kV 25 years qualification limit.

10 LW sound cable samples and 10 LW cable samples with bare strands (discontinuity of

the conductor layer) were submitted to high voltage ramp test up to breakdown. 25 LW sound cable samples and 25 LW cable samples with bare strands were submitted to high voltage ageing test up to breakdown.

From these results, a statistical study enabled to determine the n factor of the aluminium conductor cable with and without bare strands.

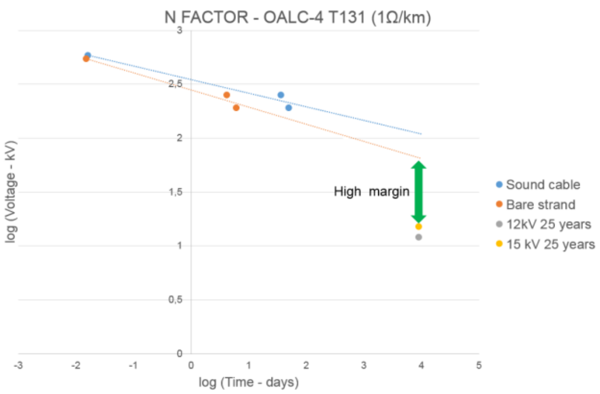

Figure 7: N-factor statistical study of aluminium conductor cable, with and without bare strand (references [3] & [4])

The n factor value of aluminium conductor cable was found very high, even when containing bare strand. Equivalent evaluated life time at 15kV has been calculated at 0.26 million of years. This demonstrates the high margin of OALC-4 aluminium conductor cable.

4.2. Hydrogen tightness

Additional characterization tests were performed to better evaluate the aluminium conductor cable tightness versus hydrogen.

A paper study was performed prior to the aluminium conductor cable development, that demonstrated the robustness of this new cable variant in terms of tightness against hydrogen penetration: additional tests were performed to complete this paper analysis with experimental results.

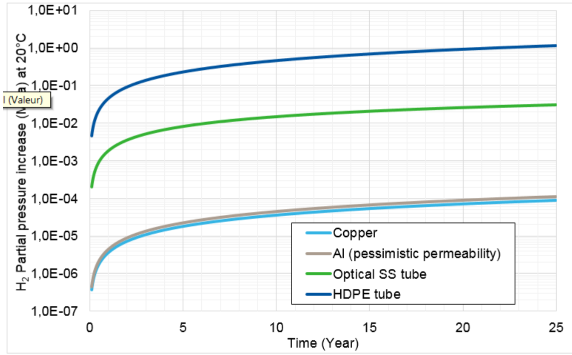

Figure 8: Extract of paper study – Hydrogen partial pressure built up over time in optical tube, copper and aluminium conductors

A first test demonstrated the transversal cable tightness under hydrogen atmosphere.

Copper and aluminium tubes have been placed into sealed enclosures. Tubes were filled in with hydrogen. A fibre spool was placed in each enclosure and monitoring of its attenuation was performed, to detect if the hydrogen inserted inside the tubes succeeded to diffuse through the copper or aluminium tubes and to reach the fibre.

This test was performed over 190 days. No attenuation increase was measured on any of the two fibres. This demonstrates the good hydrogen tightness of copper and aluminium tubes.

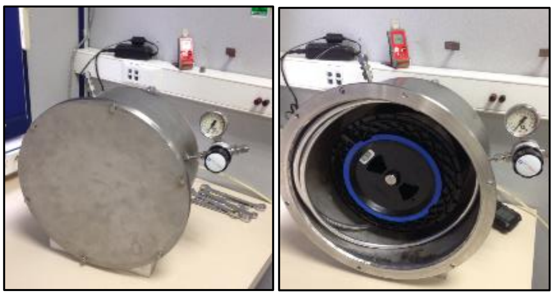

Figure 9: Testing enclosure for hydrogen transversal tightness test

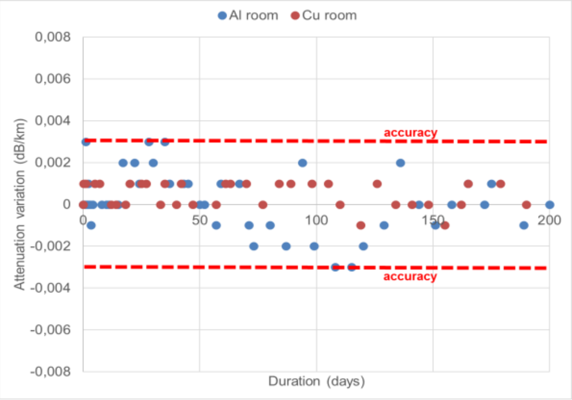

Figure 10: Testing results for hydrogen transversal tightness test

A second test was performed to demonstrate the longitudinal tightness of aluminium conductor cable against hydrogen ingress when cable is cut on the sea-bed.

A LW cable sample, containing 3 jointing boxes at 50m from each other, was prepared. In each joint, a 3km fibre spool was integrated, acting as an hydrogen detector in case hydrogen reaches the joint. The sample was then immersed in a tank with salt water for 7.5 months, with aluminium from cable extremity exposed to salt water and corrosion effects. Attenuation of the sample at 1240nm was constantly monitored.

No attenuation increase was measured during the test. Hydrogen ingress inside the cable sample was thus very limited and hydrogen did not reach any of the 3 jointing boxes.

Figure 11: Testing device for hydrogen longitudinal tightness test

4.3. Corrosion with shunt fault

An additional test was performed to characterize the aluminium conductor cable with shunt faults under corrosive environment. 10 cable samples with shunt faults were immerged inside salted water at 48°C for 16 months. Due to the presence of shunt fault on the samples, the aluminium layer is directly exposed to heated salt water and potential corrosion effects. No damage on aluminium was observed after the test.

Figure 12: Sample dissection after corrosion test on cable sample with shunt fault

5. SEA TRIAL

To complete this comprehensive qualification and characterization testing programs, a sea trial was performed, to further demonstrate the adequacy of OALC-4 aluminium conductor cable with laying and recovery operations and constraints.

A sea trials area was chosen off Portugal in North Atlantic. The tested sample was composed of aluminium conductor cables (tested cables), jointed at its extremities with copper conductor cables to have sufficient cable length for the laying and recovery operations in deep sea. A loop box was assembled at one of the sample extremities to enable the optical follow-up of this sea trial.

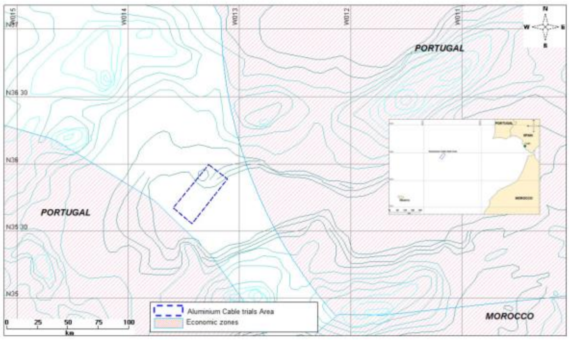

Figure 13: Aluminium conductor cable sea trial area

8.5km of OALC-4 aluminium conductor cable and joints have been laid and recovered down to 4778m water depth.

During laying, the ship speed was slightly increased and the straight-line catenary was established. During recovery, the pay-out was stopped, and the ship position was adjusted so that the cable was maintained at its NOTS for 48 hours.

No incident was reported during both loading and sea trial operations. No behaviour difference was found between copper and aluminium conductor cables during loading, laying, recovery and stand-by operations.

Optical and electrical results were compliant with requirements at all measurement stages.

6. OTHER FIELDS OF APPLICATION FOR SUBMARINE ALUMINIUM CONDUCTOR CABLE

The first aluminium conductor cable development was performed on 1 Ohm/km OALC-4 (17mm) cable. Any other repeatered cable from OALC- cable family can then be adapted to integrate aluminium composite conductor instead of copper. The cable design can also be adapted easily to accommodate high fibre count inside the optical module, similar to copper conductor cable.

Another obvious field of application is unrepeatered cable market, where requirements in terms of ohmic resistance are much less stringent and where aluminium specification in terms of electrical resistivity value could thus be much higher, resulting in even cheaper aluminium.

An additional field of application is Oil and Gas optical cables, where some of the products, as DC/FO double conductor cables, have lots of conductor material. Thus, replacing copper by aluminium would have a direct significant impact on the product cost.

7. CONCLUSION

In conclusion, the aluminium conductor cable design provides a lower cost solution, with same technical performances as copper conductor cable.

Thanks to a comprehensive qualification and characterization test program, we fully characterized the performances of 1 Ohm/km OALC-4 aluminium conductor cable. This program demonstrated the full compliance of the product to ITU-T G976 [2] and ASN qualification standards. It also demonstrated the perfect suitability of the 1 Ohm/km OALC-4 aluminium conductor cable for ultra-long haul deep sea transmission systems up to 15kV for 25 years.

Several other fields of applications could directly benefit from this new technology, including submarine unrepeatered optical systems market and oil & gas market.

8. GLOSSARY

DCR: Direct Current Resistance
OALC: Optically Amplified Line Cable
LW: Light Weight Cable
SA: Single Armour Cable
DA: Double Armour Cable
NOTS: Nominal Operational Tensile Strength
NTTS: Nominal Transient Tensile Strength
UTS: Ultimate Tensile Strength
JB: Jointing Box
EB: Extremity Box
UJ: Universal Joint
DC/FO: Direct Current / Fibre Optic Cable

9. REFERENCES

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