A NEW HIGH-VOLTAGE INTERFACING LINER TO IMPROVE REPEATER THERMAL PERFORMANCE

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Abstract: The evolution towards higher capacity systems inevitably increases the electrical power dissipation in submerged plant, which in turn demands that the heat-transfer efficiency of all parts of the repeater should be optimised in order to minimise the working temperatures of the critical components. One very significant interface for heat transfer is the electrically insulating liner between the outer housing of the repeater, which is at local earth potential, and the repeater internal units which may be many thousands of volts different from the outer housing. Up to now, most suppliers have used low-density polyethylene (LDPE) as the material for this liner. While LDPE has excellent electrical insulating properties its thermal conductivity is low, resulting in a significant thermal gradient across this interface. To reduce this temperature rise, a new material has been evaluated and is undergoing qualification for this application. Tests have shown that a filled elastomer can provide electrical insulating properties similar to polyethylene while providing a much higher thermal conductivity. A candidate material has been tested extensively in terms of its electrical, thermal and long-term ageing/stability performance. This material has now been fully trialled and its suitability for use in submerged equipment has been confirmed, with the expected improvement in thermal performance of the repeater.

1. THERMAL FLOW THROUGH A REPEATER LINER

The temperature rise T from the outside to the inside of the electrical insulating liner is related to the total electrical power W dissipated in the repeater by the simple formula:

$$T = W/C_{th} \quad (1)$$

where the thermal conductance C_{th} is a function of the thermal conductivity, geometry (area and thickness) and contact effects across this particular thermal interface.

Measurements of this temperature difference for a given power dissipation have been reported in the paper on the modelling and trialling of the thermal effect of repeater burial (ref. 1), which has also been published at this conference.

The repeater burial trials showed a consistent temperature increase from the outside of the seacase to the inside of the polyethylene liner of between 5°C and 6°C for a repeater dissipating 80W of electrical power. This therefore gives a C_{th} across this thermal interface of about 14.8W/K.

This thermal conductance figure indicates that as repeater electrical powers increase to 150W or more, the temperature rise across this interface alone will be over 10°C. It would therefore definitely be worthwhile to reduce this temperature difference by replacing the polyethylene liner with one made from a material with a significantly better thermal conduction performance

2. IMPROVING THE THERMAL PERFORMANCE OF THE LINER

Higher thermal conductivities can be achieved in electrical insulating materials by the addition of ceramic fillers. However, the addition of such fillers can be difficult to distribute within a polymer base material and can have detrimental effects on the subsequent processes.

The current manufacturing method for the PE insulation sleeves is to extrude the material as a tube. Such a process requires the polymer to be heated until molten and then extruded through a die under vacuum to form a tube which is then pulled through a series of water-cooling baths to create a continuous cylinder. As high capacity repeaters grow in size to accommodate more and more electronics, the forming of larger diameter thin-walled structures becomes more difficult to achieve.

The addition of fillers to extruded polymers such as polyethylene introduces the following additional potential problems.

- Dispersion and distribution of the filler is affected randomly by the extrusion process and so material thermal and electrical properties can vary throughout the cylinder structure.

Fig. 1 Bad Dispersion and/or Distribution of the Filler after the Extrusion Process

- Fillers dramatically change the extrusion process parameters of the polymer due to changes in viscosity and specific heat. This can result in poor dimensional stability of the tube, poor surface finish, excessive stress within the material, and premature cooling within the die resulting in clogging and binding.
- Fillers can be abrasive causing excessive die and tool wear.
- High percentage fill can reduce the elasticity of the base material turning it biscuit-like, and making the sleeve too fragile to handle and vulnerable to damage once manufactured.

By adopting compression moulding rather than an extrusion process it is possible to ensure good dispersion and distribution of the ceramic filler, because this is achieved at the sheet milling phase. Unwanted turbulent disruption of the filler distribution within sleeve moulding is limited as the tool cavity is already 90% full prior to pressure being applied and so the material has little distance to move.

Fig. 2 Wrapping of Sheet Material Around the Required Diameter Prior to Compression Moulding

As the material is not extruded or injection moulded to form the tube, the elastomeric material behaves more homogenously, resulting in less residual stress within the material and a more dimensionally stable product.

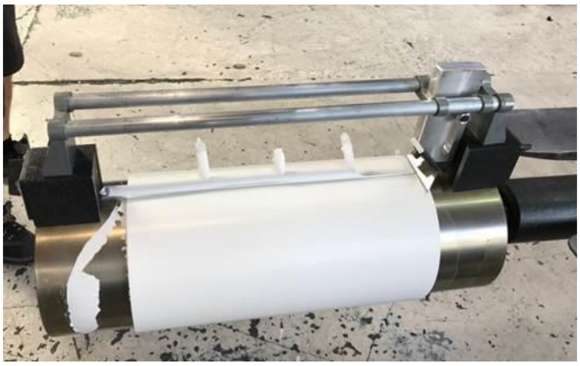


Fig. 3 Machining Away of Surplus Material After Compression Moulding

This process results in a much more uniform dispersion and distribution of the thermally-conducting filler material in the final liner product.

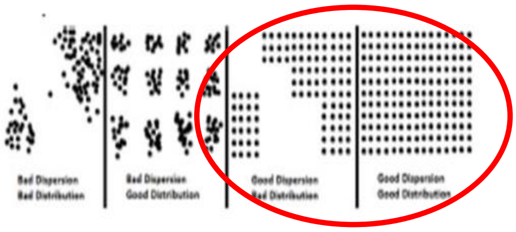


Fig. 4 Typical Dispersion of the Filler in the Finished Liner

3. THERMAL CONDUCTIVITY OF THE NEW MATERIAL

Thermal conductivity measurements were carried out on 100mm-square plaques with the same nominal thickness as the liner itself. These measurements were done by a specialist thermal measurements facility in accordance with the ISO standard plane-source measurement method (ref. 2).

A total of ten separate samples were measured, and five separate measurements were made on each sample to check the consistency of the measurement technique and the uniformity of the new material.

In summary, the mean thermal conductivity measured was 1.67 W/m/K with a standard deviation of 0.04W/m/K or 2.5%. All 50 measurements made gave figures higher than 1.57 W/m/K.

The thermal conductivity of LDPE about 0.33 W/m/K, so its replacement by the new material could result in a potential reduction in temperature rise by up to a factor of 5, all other things being equal. It was therefore definitely worthwhile undertaking a full evaluation of its suitability for this application, as described in the following sections.

4. ELECTRICAL BREAKDOWN PERFORMANCE

It is clearly essential to confirm by thorough qualification testing that this potential new liner material had a DC insulation performance as good as, or better than, the low-density polyethylene which it was replacing.

The maximum long-term (>25year) voltage which can be experience by submerged plant is currently 12kV, and in systems in the near future this is likely to increase to 15kV or higher. The thickness of the liner is typically 5mm and so it is necessary to demonstrate that the liner material will survive a DC electric field of 3kV/mm for a minimum of 25 years. Plaques with a thickness of 1mm were produced to quantify the voltage/time relationship for this material.

For a DC voltage V applied for a time t before breakdown occurs, the following empirical formula has been widely used and accepted:

$$t.V^N = k \quad (2)$$

where N and k are constants for a particular material. Once they are established for the loaded silicone, equation (2) can then be used to confirm the performance of the liner under working conditions. The most time-efficient way to establish these constants is to ramp several different 1mm plaques of the material up to breakdown at several different ramp rates.

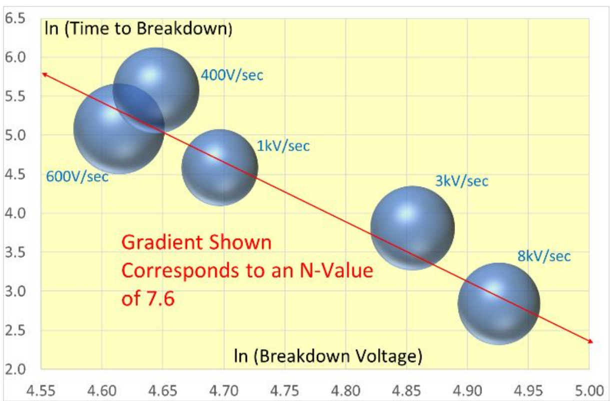
For a voltage which varies with time, equation (2) needs to be extended to:

$$\int V^N.dt = k \quad (3)$$

and for a ramped voltage which simply increases linearly with time until breakdown occurs, the integration can be performed quite easily to give:

$$(V_B)^N.T_B = (N+1).k \quad (4)$$

where V_B is the breakdown voltage and T_B is the time to breakdown on the ramp. A logarithmic plot of T_B against V_B will therefore have a negative slope with gradient N. There will inevitably be some spread in breakdown voltages and times, but if a large enough number of nominally identical samples are measured at different ramp rates, both N and k can be estimated with sufficient accuracy and confidence limits for reliable lifetime calculations to be made. The results obtained from these tests are shown in the following graph, in which the size of the circles correspond to the spreads within each set of ramp-rate tests.



Graph 1. Logarithmic Plot of Time to Breakdown Against Breakdown Voltage at Different Ramp Rates

There were sufficient results taken for a sensible linear regression analysis to be carried out on the data, and this enabled a standard deviation of 1.03 to be estimated, in the quoted N-value of 7.6. This means that there can be 99.7% confidence that the true figure for the N-value of this material is better than the figure of 4.75 generally taken as the N-value for LDPE.

The k-value derived from these results gave a figure of 4.3E16 with a standard deviation of 1.4E16. Inserting these figures into equation (2) for a 5mm-thick liner gives lifetimes under service conditions which are well in excess of the current 25-year requirements.

High-voltage qualification testing on this material is still ongoing at the time of publication, because this testing includes steady-voltage DC tests which inevitably take some time to complete. But all results so far indicate that this material has an excellent high-voltage performance, which may actually be better than that of the LDPE which it will replace.

5. ACCELERATED AGEING AT ELEVATED TEMPERATURES

The long-term chemical stability of all materials used in submerged plant needs to be thoroughly quantified and proved. As well as the requirement that the liner material should not change in any way that degraded its electrical insulation performance or its thermal conduction performance over the system lifetime, there is also the specific requirement that none of the internal repeater materials should outgas hydrogen over the system lifetime to the extent that the hydrogen might have an adverse effect on any critical repeater components.

The liner comprises the largest single quantity of polymeric material within the repeater by some margin. At a density of 1370kg/m^3, its total mass is around 2.8kg, about 50% higher than that of a LDPE liner simply because of its increased density.

Details regarding the issues involved in the outgassing of hydrogen from internal repeater components are covered in more depth in a separate paper at this conference (ref. 3), and so for now it is sufficient simply to compare the performance of the new material and low-density polyethylene in this respect.

	LDPE	Silicone
72-day, 80° Outgassing	8.4E-6 cc/gm/day	2.9E-6 cc/gm/day
40/80 Activation Temperature	7300°	12000°
25-year Outgassing at 20°	2.11gm H_2	0.19gm H_2

Table 1. Comparative Hydrogen Outgassing Performance of Low-Density Polyethylene and the New Liner Material

Table 1 shows that the silicone produced slightly less hydrogen per unit mass in a standard 72-day 80°C outgassing measurement, and because of its higher activation temperature as measured in 80/60/40°C tests, the total hydrogen that might be produced in a repeater over 25 years at ambient temperature or below is an order of magnitude than might be expected from the existing LDPE. This is also indicative of a higher general chemical stability in the silicone.

It should be mentioned that the hydrogen that might emanate from the LDPE is still very low and would easily be handled by the hydrogen getter within the repeater, but the fact that the silicone has a better performance than the LDPE in this respect too is another point in favour of adopting the silicone for this application.

6. DIRECT MEASUREMENTS OF REPEATER THERMAL PERFORMANCE

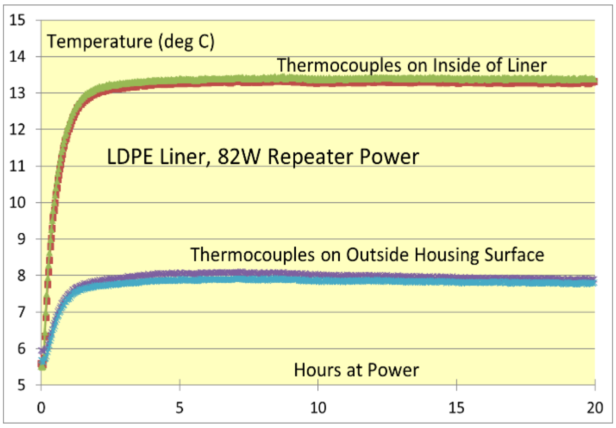
The obvious demonstration of the improvement (i.e. reduction) that the silicone liner material would make to the temperature rise from the outside to the inside of the repeater would have been to have assembled a repeater with a single-piece silicone liner and to have measured directly the temperature difference between the outer seacase and the repeater internals. This could then be compared with the temperature rise between the seacase and internals with a LDPE liner, which would be expected to be significantly higher.

Unfortunately, the tooling to manufacture a full-length liner was not available in time for such a liner to be incorporated as part of the repeater thermal trials which took place during 2018. However, it was possible to manufacture a cross-sectionally representative trial liner in three shorter sections as shown in the following figure.

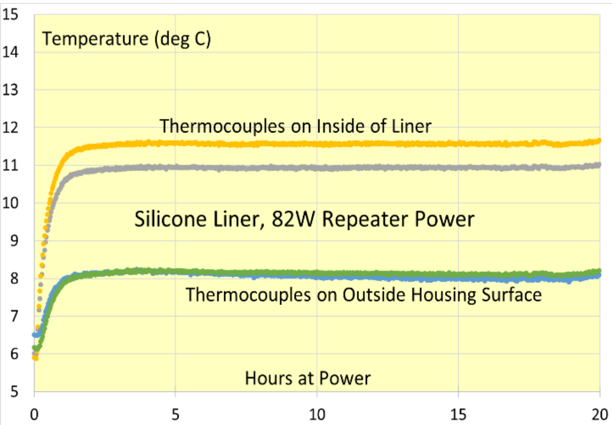
Fig. 5 Silicone Liner in Three Sections for Initial Thermal Trial

It was realised that, because of the polyimide tape which was used to join together the three sections of the silicone liner, the contact between the liner and the repeater seacase would be non-uniform and not as effective as it would be with a single-piece sleeve, regardless of the material. This reduction in the contact efficiency would reduce the thermal conductance to some extent, so that the full improvement achieved by the use of a silicone liner would not be seen directly. It was, however, still thought worthwhile carrying out a set of thermal measurements with the composite tube shown in fig. 5 to see how much improvement would be obtained.

For each test, the repeater was placed in a constant-temperature water bath and powered at 82 Watts. Temperatures at key locations were monitored and the temperatures at either side of the LDPE and silicone liners are shown in the following graphs.



Graph 2. Temperatures on Either Side of LD Polyethylene Liner



Graph 3. Temperatures on Either Side of Silicone Liner

The time to reach thermal equilibrium in these tests was much less than that for a repeater buried in sediment (ref.1), as would be expected. After approximately 200 minutes there was a steady temperature difference across each liner, as is clear from the graphs. It was noted that the two thermocouples on the inside of the LDPE liner showed very similar temperatures, whereas for the situation of the silicone liner there was a significant difference. This indicated that, as suspected, there was variability in contact from the repeater internals to the liner, very probably because of the polyimide tape required for this preliminary trial.

Despite this thermal contact problem, it can be seen from the graphs that the temperature rise across the liner was significantly lower with the silicone than with the LDPE. Those mean temperature differences were 3.15°C and 5.42°C respectively: an improvement of 72% in the thermal conductance.

It is possible to make an estimate from these results as to how much improvement will be obtained when the internal and external contact to the silicone liner is as good as that to the LDPE liner, and also to check whether the presence of the polyimide tape accounts for the actual result obtained with the silicone liner.

The contact/area thermal efficiency with the LDPE liner was 56%: - a credible and good figure in view of the inevitable variability in temperature and contact within the internal units. It is reasonable to assume that a continuous silicone liner would have a similar or better thermal contact efficiency, and based on the measurements reported in section 3 this would result in an effective conductance of 76.6W/K, compared with 15.1W/K measured for the LDPE liner.

The actual conductance deduced from graph 3 is approximately 26W/K, and this reduction in conductance can be accounted for by an air gap of about 0.24mm in series with the liner. Since the thickness of the polyimide tape was around 0.26mm, this would seem to account perfectly for the result obtained.

It can therefore be concluded that replacing the LDPE liner with a continuous silicone liner would improve the thermal transfer through this interface by a factor of over 400%, the same as the difference between the thermal conductivities of the 2 materials. For an 82W repeater the temperature difference would therefore reduce from 5.4°C to less than 1.1°C, with proportional reductions for higher-power repeaters.

7. SUMMARY OF THE ADVANTAGES AND SUITABILITY OF THE NEW MATERIAL

Extensive laboratory testing and trialling has shown that a filled elastomeric liner has a superior performance to the low-density polyethylene liner currently used as the high-voltage interface in submerged plant.

The temperature rise across this liner in an 80W repeater should reduce from over 5°C to around 1°C, with proportional reductions in repeaters with higher electrical powers. This will have a significantly positive impact on the reliability and lifetime of pump lasers and other critical repeater components.

The N-value for high-voltage DC conditions has been measured by ramp tests to be around 7.6. This is well above the figure of 4.75 generally used for polyethylene components, and indicates an excellent long-term electrical reliability performance.

The chemical stability of the material, as measured by hydrogen outgassing at elevated temperatures, has again been found to be superior to that of polyethylene.

The processing of the material, using compression moulding as opposed to extrusion, has several advantages especially as the housings for submerged plant increase in size.

For all of these reasons, it is intended to incorporate the silicone liner into our future submerged equipment.

8. REFERENCES

[1] I Watson, L Foulger, D Walters and P Worthington: 'Evaluation and Optimisation of Thermal Management in High-Power Repeaters', SubOptic 2019.
[2] ISO 22007 - 2:2015 - Plastics-Determination of thermal conductivity and thermal diffusivity – Part 2: Transient plane heat source (hot disc) method.
[3] D Walters and P Worthington 'The History and Science of Hydrogen in Submarine Networks', SubOptic 2019.