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EVALUATION AND OPTIMISATION OF THERMAL MANAGEMENT IN HIGH-POWER REPEATERS

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Abstract: The current trend towards high capacity and high fibre count systems is driving the demand for high-power repeaters dissipating an electrical power of 80W or more. The inevitable rise in temperature of the pump lasers and other key components that will result from this increase in power needs to be understood and quantified in order to ensure that the high reliability required for submerged plant can be maintained. For a buried repeater, one of the most significant thermal interfaces is the heat flow out of the seacase and into the seabed through the burial sediment. This can result in one of the largest rises in temperature and is generally the least well-defined and understood of all the thermal flow-paths from the critical components to seabed ambient. Work has been done on theoretical modelling and direct practical measurements, including a full-scale land-based repeater burial trial, to obtain a much better understanding of this key thermal interface. There has been good agreement between the analytical model and the results from practical trials, so that accurate temperature rise predictions can now be made for a given set of repeater housing materials and dimensions, and burial conditions.

1. THERMAL FLOW FROM A BURIED REPEATER

The heat produced in a repeater buried in sediment will flow into the infinite heat-sink of the seabed.

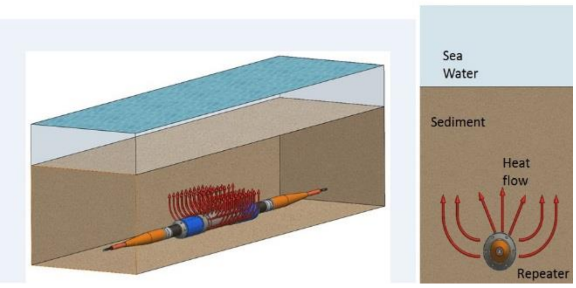


Fig. 1: Thermal Flow from a Buried Repeater

Physically, the repeater is a horizontal metal cylinder of known dimensions (length L and diameter d), buried in sediment at a depth H below the seabed. The thermal conductivity C of the sediment will be more than an order of magnitude lower than that of any metal repeater seacase material. The ends of the cylinder will be attached to cables via metal couplings. Some heat will flow though those couplings but most will flow into the sediment from the curved surface of the repeater.

The total electrical power in watts divided by the temperature difference between the seabed and the outside of the repeater seacase gives the thermal conductance C_{th} (measured in watts per degree) from the repeater to the sea. For a given set of repeater dimensions, burial depths and sediment conductivities, C_{th} can be calculated theoretically by treating the seacase as an isothermal surface and solving Poisson’s equation for those conditions.

This calculation could be done by finite-element or other numerical techniques, but a clearer mathematic model of the physical system can be obtained by an analytical approach.

2. ANALTYICAL MODELS OF THERMAL FLOW

For a model in which the sediment is considered as a medium which does not significantly absorb heat itself, but simply conducts it to the infinite heat-sink of the seabed, the solution of Poisson's equation gives the following expression for the thermal conductance:

$$C_{th} = 2\pi C.L/COSH^{-1}(2H/d) \quad (1)$$

This formula is the thermal equivalent of the electrical analogue for the capacitance of a cylinder of length L and diameter d at a distance H from an infinite conducting plane.

Equation (1) is the correct one to use for the situation of shallow burial, where the burial depth is comparable to or less than the repeater diameter. But for depths greater than that, which would always be the case for deliberate repeater burial, it will give pessimistic (i.e. too low) figures for conductance because in that situation the heat flow into the sediment in all directions needs to be considered, and the sediment will be absorbing the heat as well as conducting it, eventually, to the seabed.

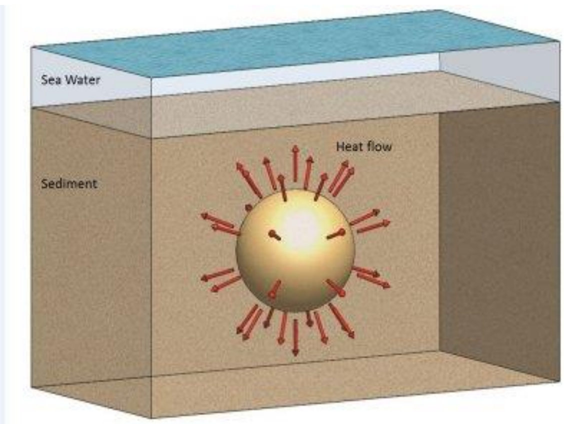


Fig. 2: Radial Heat Flow from a Sphere

For a sphere with diameter D feeding heat into an effectively infinite uniform medium with thermal conductivity C, simple integration gives a thermal conductance to infinity of:

$$C_{th} = 2\pi D.C \quad (2)$$

3. THE CONCEPT OF 'EQUIVALENT THERMAL DIAMETER', ETD

The thermal conductance C_{th} is simply the total electrical power W divided by the temperature difference T between the outer surface of the repeater and the infinite heatsink of the seabed.

$$C_{th} = W/T \quad (3)$$

In an experiment or trial in a material of known thermal conductivity, W can be set and T can be measured, to enable C_{th} to be found from equation (3).

A value of 'Sphere diameter' D can then be calculated from equation (2), and this is referred to as the 'Equivalent Thermal Diameter', ETD, of the repeater.

$$ETD = C_{th}/(2\pi C) \quad (4)$$

The ETD is the diameter of a sphere that would have the same thermal conductance to the seabed as that of the repeater, when buried in sediment with the same uniform conductivity C.

The repeater is of course a cylinder rather than a sphere, so it will not transmit heat as uniformly into the sediment as a perfect sphere would. But nevertheless, it would seem to be reasonable to calculate the diameter of a sphere that would have the same geometrical surface area as the cylindrical repeater and this should provide a reasonable (though slightly high) estimate, D_{geom} of the value of the ETD as given by equation (4). From simple geometry:

$$(D_{geom})^2 = d.(L + d/2) \quad (5)$$

If this analytical approach is broadly correct, then D_{geom} and ETD should be close to each other, certainly to within much better than an order of magnitude.

It was considered prudent to test the validity of this analytical theoretical approach by a small-scale experiment before embarking on a full-size repeater burial trial.

4. INITIAL SMALL-SCALE TEST

A 1/10-scale metal housing was machined, with a sealed central cavity that contained electrical resistors that could be powered up to about 11 watts. Four-wire electrical connections were made to the resistor and a thermocouple was attached to the outside centre of the housing.

Fig. 3: One Tenth-Scale Housing

The housing was buried in a tank of wet sand, as shown in fig. 4.

Fig. 4: Small-Scale Burial Test

The temperature at the housing surface rose as soon as the electrical power was applied, and after approximately 90 minutes it had settled to a 'reasonably asymptotic' level, at around 1.6°C per watt of power.

The results from a number of these small-scale tests gave figures consistent with the theory described in sections 2 and 3, for sand with a thermal conductivity of around 2.5W/m/K and for the value of ETD comparable to that of D_{geom}. This gave confidence that a full-scale burial trial under controlled conditions would be a useful exercise to confirm the key factors affecting repeater temperature rise in service, and to enable meaningful predictions of temperature rise to be made.

5. LAND-BASED BURIAL TRIAL

It was decided to bury an experimental repeater, with thermocouples monitoring key locations inside and outside the repeater, in a large tank that was available as part of a test facility.

Fig. 5: Construction of Full-Scale Burial Trial

Fig. 5 shows the repeater lying 1m above the bottom of the tank prior to the operation of completion of the filling of the tank with a total of approximately 35 cubic metres of builders' sand.

A water bath maintained at a constant temperature was then placed over the burial arrangement to simulate the seabed heatsink.

Fig. 6: Constant-Temperature Water Bath, Prior to Covering

It was of course necessary to know the thermal conductivity of the sand surrounding the repeater, and the positions of 8 sensors to enable that to be done are shown in the following diagram.

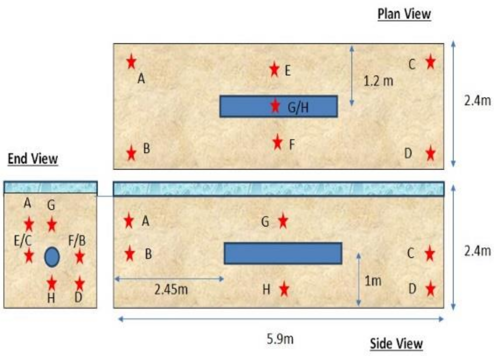


Fig. 7: Positions of Thermal Conductivity Sensor Spheres

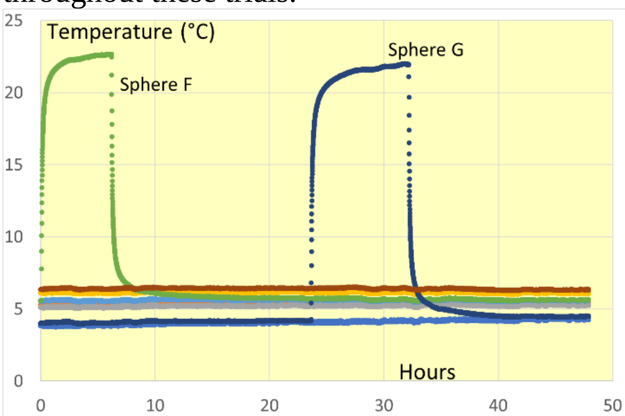
The principle used for these conductivity sensors, which also acted as temperature sensors during the repeater powering trials, is described in the following section.

6. MEASUREMENT PRINCIPLE FOR THERMAL CONDUCTIVITY

The 8 conductivity sensors were 30mm-diameter metal spheres containing electrical resistors to be used as heaters, with thermocouples mounted on the surface of the sphere. A typical sphere is shown in the following photograph.

Fig. 8: Thermal Conductivity Sensor Sphere

Four-wire electrical connections were made to the resistors so that measurements of current and voltage could be made, and this gave an accurate figure for power dissipation, which was adjusted to be close to 6W. Each k-type thermocouple was connected to a channel in a multi-channel data logger, which also monitored all other temperatures and voltages of interest throughout these trials.



Graph 1: Temperature Rises on Powering of 2 of the Sensor Spheres

Graph 1 shows the temperature-rise characteristic of two of the conductivity-measuring sensor spheres. The thermal conductivity of the burial material in the vicinity of each of the sensor spheres was measured by powering the sensors one at a time, with no power applied to any of the other sensors or to the repeater.

As can be seen in the graph, the temperature at the surface of the spheres rose rapidly at first and then after some hours it settled to a point where a steady-state asymptote could be deduced. This characteristic is what would be expected from a solution of the diffusion equation in a system with 3-D spherical symmetry.

From equation (3), dividing the power dissipated by the rise in temperature of the sphere gives its thermal conductance C_{th} to infinity. The conductivity of the medium in its vicinity can then be found using equation (2) since in this case the sphere diameter D is known accurately to be 30mm.

It was found quite consistently that the rise in temperature of any buried sphere, 40 minutes after application of the power, had reached around 88% of its final ‘Asymptotic’ value. This enabled the thermal conductance measurements to be made in a reasonably short time, so that the conductivity in the vicinity of all 8 spheres could be measured in one day.

Sand conductivities measured using these spheres in the burial tank gave an average figure of around 1.8W/m/K, with some significant variations depending on water content and compaction, and these factors varied to some extent with time as might be expected. But the 1-day conductivity measurements could be done before and after each repeater-powering trial to give a figure for the effective conductivity of the burial medium with adequate accuracy.

7. COMPARISON WITH A CALIBRATED THERMAL CONDUCTIVITY PROBE

The method described in the last section for measuring the thermal conductivity of the burial medium was repeatable and consistent, and gave plausible results. But because it was not a formally standardised measurement method it was necessary to compare the results obtained by this method with those made using a calibrated instrument which used a recognised standardised technique.

A system using a thermal needle probe to measure conductivity by the transient line source method in accordance with ASTM D5334 (ref. 1) was hired, to compare its results with those measured by the sphere technique.

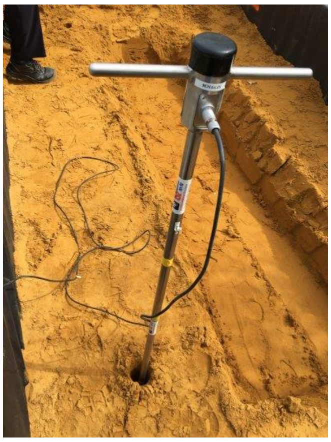


Fig. 9: Calibrated Conductivity Probe in the Burial Sand

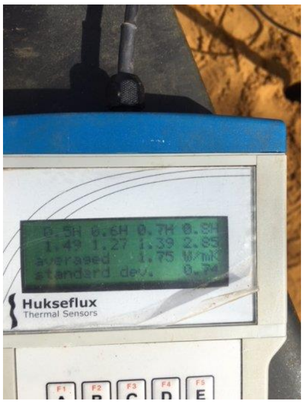


Fig. 10: Display of Measured Thermal Conductivity

This transient technique has the advantage that the measurement time is of the order of a few minutes rather than the significantly longer time needed for the sphere method, a number of separate measurements are made automatically with the probe, and the mean and standard deviation calculated.

Several measurements were made with the probe in regions of the burial pit close to the measurement spheres, and although there was quite a spread in results from individual measurements with the probe, the means of these results were remarkably close to the results from the sphere method. As an example, the displayed probe result in the photograph shows a mean of 1.75W/m/K in a region close to a sphere which gave a result of 1.79W/m/K from the 40-minute measurement method.

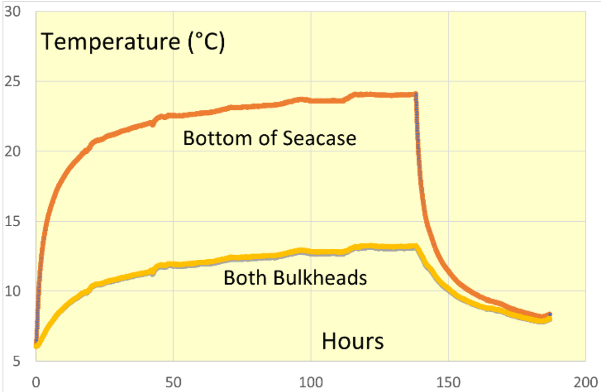
This cross-calibration check confirmed that the 40-minute measurements on each sphere gave an accurate indication of the thermal conductivity of the burial material in its vicinity. The spheres could therefore be used to give reliable figures for conductivity in the regions surrounding the repeater, and measurements using these spheres before and after repeater powering trials would enable the thermal performance of the repeater to be accurately quantified.

8. REPEATER TEMPERATURE RISE RESULTS

The buried repeater described in section 5 was powered with a current of 0.65A, resulting in a voltage drop across it of 127V and hence a power dissipation of 82.55W. Temperatures at several key locations inside and outside the repeater were all monitored by the logging system.

After 6 days of powering, all of the thermocouples showed that 'steady-state' asymptotic temperatures had been reached.

The build-ups of temperatures at the seacase centre bottom and at the end bulkheads are shown in graph 2.



Graph 2: Temperatures at Seacase Bottom and Bulkheads

The maximum temperature rises recorded at each of the locations of interest are displayed in Chart 1

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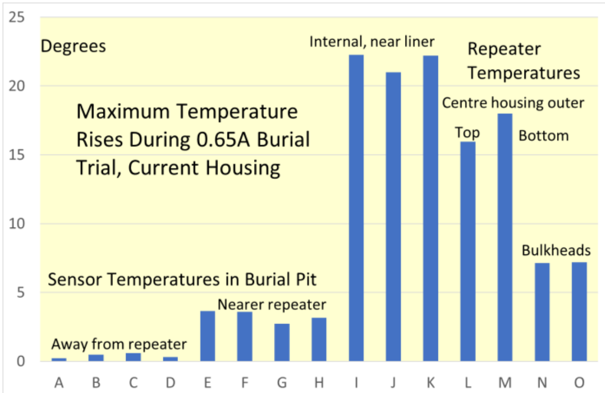


Chart 1: Maximum Temperatures Reached After 6 days Powering

It can be seen from chart 1 that the bottom of the repeater reached a slightly higher temperature than the top, and this was due primarily to the variation of sand conductivity around the repeater.

It can also be seen that there was a quite significant temperature difference between the inside and outside of the repeater. That is due mainly to the low thermal conductivity typical of polyethylene HV insulating liners, hence the desirability of qualifying a new material for this application (ref. 2). It should be noted that an insulating material on the outside of the seacase would also result in a rise in the temperature of the repeater internals. The seacase used in these trials was titanium, which like all metals has a relatively high thermal conductivity compared to insulating materials and burial sediment.

9. ETD OF THE TRIALLED REPEATER

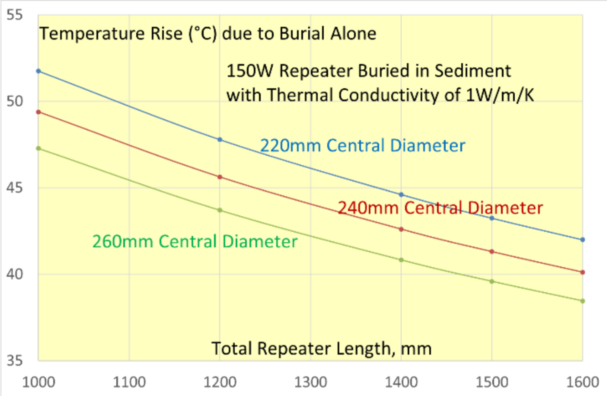
The repeater top rose in temperature by 15.9°C, giving a conductance figure from equation 3 of 5.19W/K. Corresponding figures for the repeater bottom were 18.0°C and 4.59W/K. Conductivity measurements directly above and directly below the repeater were 1.83 and 1.61, and applying equation 4 to these figures gives an ETD of 0.452m in each case.

The trialled repeater had a total surface area of 0.767m^2, taking into account the variation in outer diameter over its length. This gives a geometrical sphere-equivalent diameter D_{geom} of 0.494m, compared with the deduced ETD of 0.452m.

The derived ETD, at 91.5% of D_{geom}, therefore corresponds remarkably well to the qualitative prediction made in section 3, and this confirms the validity and accuracy of the analytical approach adopted.

10. EXTENSION TO OTHER REPEATER DIMENSIONS AND POWERS

The outside centre of the trialled repeater seacase rose in temperature by ~16°C above ambient when powered at 82.6Watts and buried in a medium with a thermal conductivity of 1.83W/m/K. Because of the good agreement between the analytical predictions and measured results, it is now possible to predict temperature rises for different repeater dimensions, powers and sediments conductivities.
This can be done simply by making the reasonable assumption that, for a cylindrical repeater, the ETD will be close to around 90% of D_{geom} in all practical cases. Results of some of these predictions are shown in the following graph.



Graph 3: Seacase Temperature Rise Predictions for Different Repeater Dimension Options

Graph 3 shows the predicted temperature rises against length for three different central seacase diameters, for a 150W repeater buried in sediment with a conductivity of 1W/m/K.

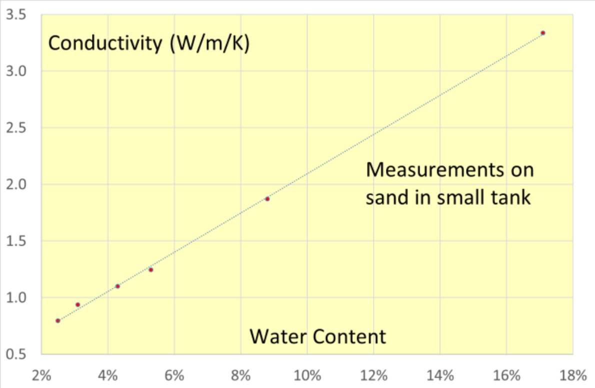
It needs to be remembered that these predicted temperature rises are for a buried metal seacase alone. All other significant thermal paths, such as the insulating liner (ref. 2) or an additional coating on the outside of the repeater, would result in further temperature rises additional to those shown in the graph.

11. SEDIMENT CONDUCTIVITY IN PRACTICE

The major uncertainty in any estimation of the rise in temperature due to burial of a repeater under working conditions is very likely to be the figure for the thermal conductivity of the burial sediment.

Ocean sediment is generally regarded as having a conductivity of 1W/m/K or more, and this is consistent with the measurements made during these burial trials, though figures down to 0.8W/m/K have been reported (ref. 3).

Thermal conductivity has generally been considered to be strongly dependent on water content, and so some measurements using the small-scale tank described in section 4 were carried out to test this, using one of the sphere sensors in sand at varying degrees of saturation. The result obtained are shown in the following graph.



Graph 4: Variation of Thermal Conductivity with Water Content

It is clear from this that at the levels measured there is a linear relationship between water content and sand conductivity. However, to know accurately the thermal conductivity of a medium in which a particular repeater was buried, it would of course be necessary either to measure that directly by some means or to know the water content of the actual sediment surrounding the repeater.

In the absence of a definite figure, a value of 1W/m/K should be assumed, as was done for the graph in section 10.

12. CONCLUSIONS AND COMMENTS

Full-scale repeater burial trials and thermal conductivity measurements have been carried out to quantify the effect of repeater burial on the temperatures of critical components in repeaters operating at a high electrical power

The trials have shown excellent agreement between the measured results and an analytical model for deep burial which shows the temperature rise of the repeater to be independent of depth and related to the surface area of the repeater.

It is clear from these trials and analyses that thermal design of the repeater, and the thermal effect of repeater burial, are important factors to take into account as repeater electrical powers increase. The rise in temperature of a 150W repeater simply resulting from the burial of the metal seacase alone is likely to be 40°C or more, and other interfaces, such as the internal insulating liner or any coating on the outer surface of the seacase, will increase this temperature rise.

The physical design of the repeater and the qualification of critical components will always need to take into account these temperature increases.

13. REFERENCES

[1] ASTM Standard D5334 Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure.

[2] I Watson, D Walters and P Worthington, ‘A New High-Voltage Interfacing Liner to Improve Repeater Thermal Performance’, SubOptic 2019.

[3] T Newson and P Brunning, ‘Thermal Conductivity of Deepwater Offshore Sediments’, International Journal of Offshore and Polar Engineering, vol.14 issue 04, December 2004. 04-13-4-310