THE ROLE OF

LINE INSULATION MONITORS

& REDUCING COPPER LOSS ON SUBSEA ELECTRICAL SYSTEMS

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This paper discusses the fundamental processes that occur with sea water in contact with the copper conductors of a cable when an insulation monitoring device is used and further considers what happens when a similarly wetted cable with two or more insulation faults is energized with an electrical supply.

The paper will prove through theory and tests that failure of insulation resistance in a sea water environment will lead to serious and potentially catastrophic damage of the copper conductors unless the insulation failure is repaired.

LOW INSULATION RESISTANCE AS A RESULT OF DAMAGE TO SUBMERGED CABLES & UMBILICALS

With electro-hydraulic subsea production systems, the delivery of electrical power from a topsides facility to the subsea equipment is generally considered a low-risk part of the system design. For sure, there is always some electrical analysis work to do up-front that considers the selection of dc or ac (single phase or three phase) electrical power supplies, and voltage levels as well as specifying umbilical electrical parameters such as conductor sizes. The analysis is driven by the field layout, offset distances, power demands and future field expansion requirements.

Although the system design is low risk, since the electrical power system is critical for the operation of the subsea equipment, production availability will be directly impacted if the electrical system fails.

Most subsea production systems utilise a 'floating earth' electrical supply system defined as an IT (Isolation Terra) or 'unearthed neutral' system.

Further details of IT and other earthing techniques can be found in the IEC 60364 standard, but the main advantage of the IT system and why it is used extensively in critical supply applications is that it guarantees continuity of supply in the presence of an insulation fault on one of the conductors. It is well known that the most common subsea electrical failure is as a result of water ingress into a cable with degraded insulation and so an IT ungrounded system will still operate in the presence of the most common subsea failure.

A truly fault-tolerant system – or is it?

As required by the standards, an insulation monitoring device (IMD) [or Line Insulation Monitor (LIM)] is mandatory in an IT system in order to identify a first fault, so that it can be repaired before a second fault occurs.

This is important for two main reasons:

- a second insulation fault can result in high leakage currents and an electrical hazard to anyone who comes into contact with the cable or connected equipment;
- a second insulation fault, when in the presence of an electrolyte like seawater, can also result in the occurence of significant corrosion of copper conductors occurring and ultimately an electrical open circuit in the cable.

Under certain circumstances an IMD can actually cause damage to the copper conductors when there is a single fault, or problem with the insulation.

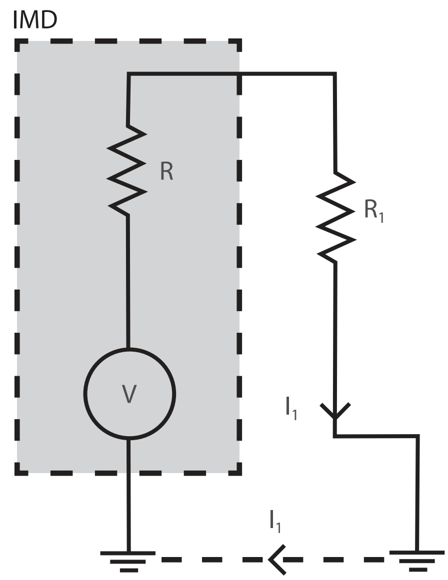
THEORY OF ELECTROCHEMISTRY & INSULATION RESISTANCE MONITORING

Firstly, let's consider the basics of electrochemistry and the inter-relationship between the movement of electrons and a resulting chemical change: when you pass an electric current through an electrolytic solution, ions (charged atoms or molecules) migrate towards the electrode of the opposite charge.

Seawater is an electrolyte due to the presence of salt (NaCl); with the dominant species of ions being sodium (Na^+) and chloride (Cl^-). Other salts are present in seawater. Additionally, a tiny amount of water (H_2O) also self-ionises (to H_3O^+ and OH^-). Pure water is very difficult to electrolyse which is why electrochemical corrosion is far more aggressive in seawater due to the reactivity of the prominent ions Na and Cl.

Electrodes can be made of inert materials that do not actually participate in chemical reaction, but instead just provide electrical current through an electrolyte (and facilitate a reaction in some cases) – i.e. they polarise to attract ions in the electrolyte where this movement of ions translates to current. Typical examples of inert materials would be graphite, platinum or gold (depending on the cell conditions). The alternative is an 'active' electrode material where the electrode actually participates in the electrolysis, where the chemical reaction translates to current through a system. Most of the materials that are used in a subsea system, such as copper, aluminium and steel, are 'active'.

Since this paper is considering what happens to subsea cables with insulation failures, let us first consider a failure in a cable that exposes one of the copper conductors to seawater – i.e. there is a low insulation resistance that is affecting one of the copper conductors only (e.g. a small hole in the insulation material). Let us also assume that the system is floating (i.e. an IT ungrounded architecture), and that an IMD is connected between the copper cable conductors and earth. On the umbilical, the nearest electrical earth to the copper conductors will likely be the steel wire armour (SWA) that is used to provide mechanical protection to the constituent components of the umbilical.



Where

V = Applied Auxilliary Voltage

R = Internal Current Limiting Resistance

R_1 = Insulation Resistance

I_1 = Leakage Current

fig.1

The principle of insulation monitoring by an IMD is to apply a voltage between the copper conductors in a cable and earth in order to measure the current that flows. The illustration above (fig.1) shows the equivalent circuit of the conductor to 'earth' connection.

The magnitude of the currents that flow are a function of the applied voltage, the frequency of the applied voltage and the electrical characteristics of the insulation material. If we keep things simple and assume that the IMD uses a dc voltage to measure the insulation resistance, then we will have a basic electrochemical cell with the electrodes being copper (the cable conductor) and steel (SWA - the nearest earth connection).

With seawater penetrating the insulation and making contact with a copper conductor then the leakage current flows through the seawater where there is dissociation of the dissolved electrolyte.

Referring to fig.2, when you apply a dc current to a seawater solution using a copper anode, the chloride ions, termed anions, will move towards this positive electrode. Whilst the positively-charged sodium ions (the cations), will migrate towards the negative electrode (the cathode) which is the steel wire armour. The migrating ions carry charge through the solution and hence help to complete the circuit.

At the copper anode one chloride ion (Cl^-) will combine with copper to form copper chloride (CuCl) and in addition some of the copper ions (Cu^+) will give up or 'donate' an electron (to form Cu^{2+}), which will then move into the seawater solution.

At the negative electrode (cathode) hydrogen ions (H^+) from the water pick up electrons to form hydrogen:

$2H^+(aq) + 2e^- \rightarrow H_2(g)$

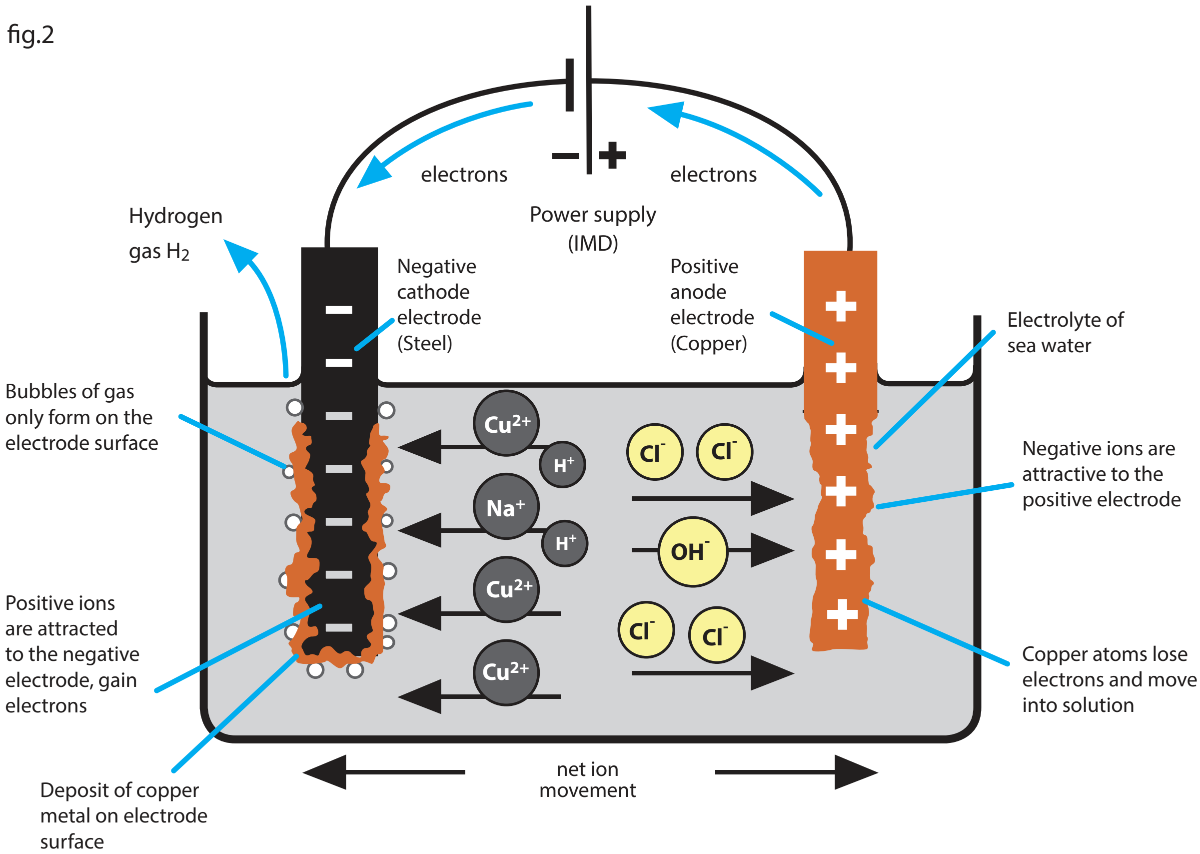
$2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$

The copper ions (Cu^{2+}) which were immobilised from the anode also pick up electrons to form metallic copper at the cathode:

$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$

In summary, the result of the IMD being connected is that the current flow being driven by the IMD results in copper ions moving into solution, thereby causing copper loss at the wetted surface of the copper conductor. In theory, hydrogen gas is also formed at the cathode (the steel wire armour).

fig.2



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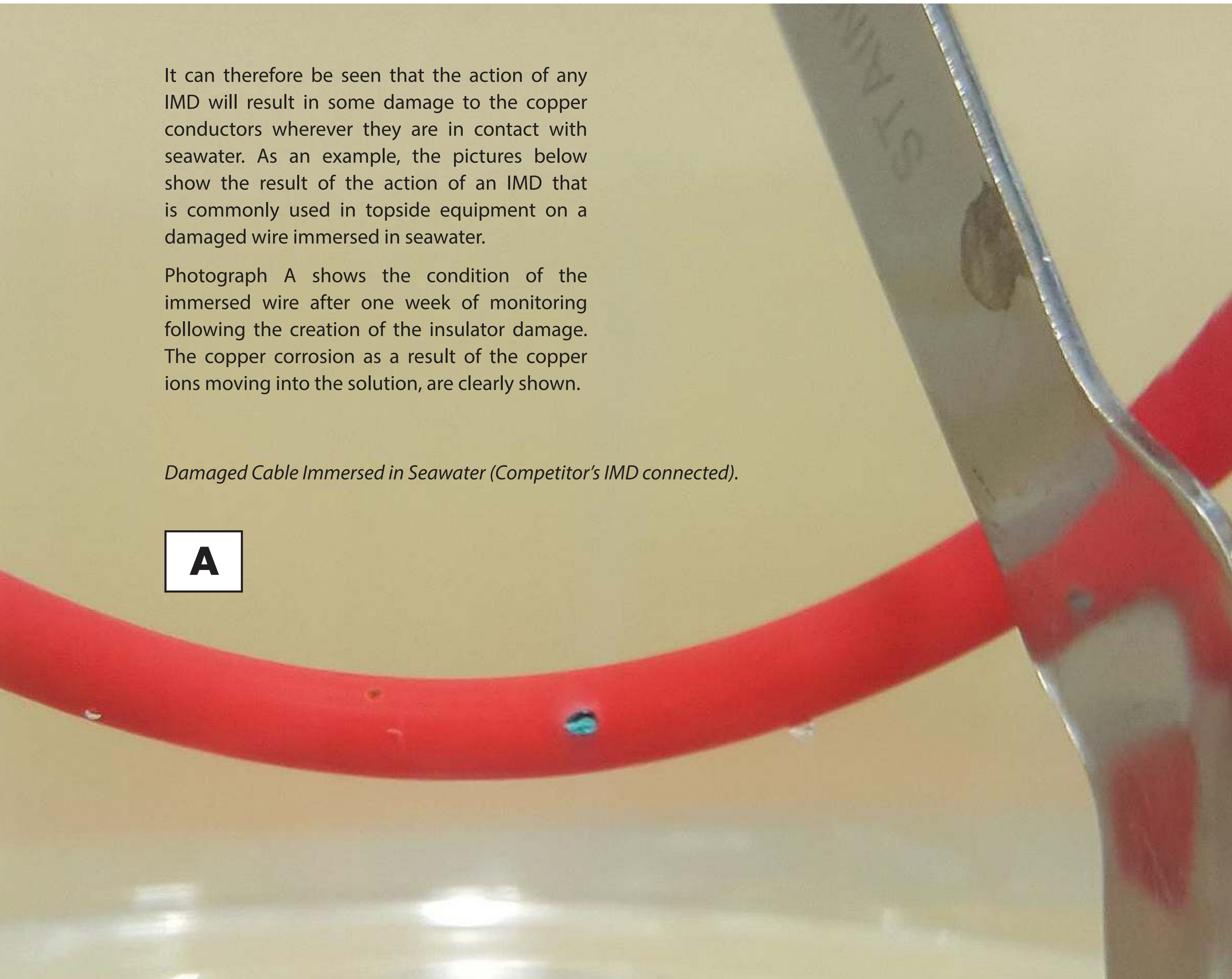
It can therefore be seen that the action of any IMD will result in some damage to the copper conductors wherever they are in contact with seawater. As an example, the pictures below show the result of the action of an IMD that is commonly used in topside equipment on a damaged wire immersed in seawater.

Photograph A shows the condition of the immersed wire after one week of monitoring following the creation of the insulator damage. The copper corrosion as a result of the copper ions moving into the solution, are clearly shown.

Damaged Cable Immersed in Seawater (Competitor's IMD connected).



A

Photograph B shows the visible corrosion on the conductor after one week of an IMD being connected. The test set-up simulated a single fault that resulted in an insulation resistance of just 30kohm.

Cut away section of the same damaged cable showing area of copper loss.

B

In any given degraded cable, the rate of loss of copper is directly proportional to the magnitude of the leakage current which is being sourced from the IMD. The copper loss is therefore clearly worse, the lower the value of the insulation resistance. The table below compares the leakage current resulting from the Viper **V-LIM** with a competitor's IMD:

Insulation Resistance	Leakage Current	
	Competitor	**Viper V-LIM**
30kΩ	190µA	120µA
100kΩ	142µA	92µA

The Viper **V-LIM** was designed with copper reduction in mind when compared with competing IMDs on the market, the result is 30% less loss. The Viper **V-LIM** can also be re-configured to reduce the applied voltage and therefore leakage current in low insulation resistance conditions, further reducing any copper loss.

As well as the loss of copper, another consequence of using IMDs when there is an IR fault, as detailed above, is the generation of hydrogen gas at the cathode. Hydrogen generation within umbilicals is a well understood phenomenon, with hydrogen appearing and being vented at the topsides. To date the source of the hydrogen has never been verified. In reality the hydrogen is likely to be as a result of a number of mechanisms covering galvanic corrosion and microbial activity. The generation of hydrogen as a result of low insulation resistance is a hypothesis that has not, as far as the author is concerned, been previously proposed.

If we accept that the use of IMDs, which are a statutory requirement in IT unearthed systems, will lead to the corrosion of the copper conductors and the generation of hydrogen gas, as the IR degrades. The obvious question that results is; why not remove the IMDs when a low IR situation occurs and manage the safety risk to personnel, via procedures and other protective measures? If a 'first fault' is detected by an IMD, then it is very likely that a similar secondary fault will impact the second conductor or wire in the power delivery system. If that occurs, then we have a completely different electro-chemical cell where the leakage current (the current through the electrolyte or seawater) is driven by the high voltage power supply that is connected between the two conductors. Remember that the IMD is creating a leakage current between the conductors and earth, but what we are now considering is the leakage between the two conductors created by the surface to subsea voltage.

ELECTRO-CHEMICAL REACTION WITH INSULATION FAILURE IN BOTH CONDUCTORS

Let us start off with a scenario in order to allow us to understand the principles of the corrosion when both electrodes are now copper.

When you apply a dc current to a seawater solution using copper electrodes, the chloride ions (anions), will move towards the positive electrode (the anode), whilst the positively-charged sodium ions (the cations) will migrate towards the negative electrode (the cathode). The migrating ions carry charge through the solution and hence help to complete the circuit.

At the anode two chloride ions (Cl^-) will each surrender an electron to the anode (which is positively charged) to form a molecule of chlorine gas, which would then fizz off the copper which is acting as the anode:

$$2Cl^-(aq) \rightarrow Cl_2(g) + 2e^-$$

At the same time, the copper (Cu) forming the electrode will also try to donate electrons:

$Cu(s) \rightarrow 2e^- + Cu^{2+}(aq)$. When the copper (Cu) gives up two electrons it forms a copper ion (Cu^{2+}) which then goes into the seawater solution.

At the negative electrode (cathode) hydrogen ions (H^+) from water pick up electrons to form hydrogen:

$$2H^+(aq) + 2e^- \rightarrow H_2(g)$$

$$2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$$

The copper ions (Cu^{2+}) which were immobilised from the anode also pick up electrons to form metallic copper at the cathode:

$$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$$

Thus, the electrolysis of seawater with copper electrodes results in a reaction at the anode which results in erosion (gradual dissolving) of the copper.

Any copper that is transferred to the cathode as a result of the reaction is unlikely to stick to the copper cathode as a result of the hydrogen gas evolution. It will far more likely be precipitated as a brownish sludge of copper metal.

The sludge is mostly, perhaps all, copper metal, which means that the anode will disappear if the electrolysis is kept up for a long period.

Thus if a high voltage dc power source is applied between two copper conductors that are both exhibiting a leakage to ground through an insulation failure, then we are very likely to see a rapid corrosion of one of the copper conductors and a resulting electrical open circuit leading to a system failure. An interesting side thought here is whether system designers at Front End Engineering Design (FEED) consider the consequences of an ac or dc supply in such a fault scenario.

So what about ac power being delivered via a submerged cable with insulation faults? The majority of published papers and forums argue that you need a dc signal in order to set up a stable cell, where the copper would corrode in the electrolyte. The argument being that the change in electrical polarity resulting from an ac applied signal results in an unstable electrochemical cell, where the copper is not given the time to dissociate into the solution before the electrical driving force is reversed. In theory, this makes sense, but what frequency is necessary to prevent the corrosion mechanism occurring?

Most subsea engineers will have experienced the contacts of a submerged electrical connector 'fizzing' if the contacts have inadvertently been left open to the seawater – typically by a missing protective plug or simply applying power inadvertently to a connector with exposed pins.

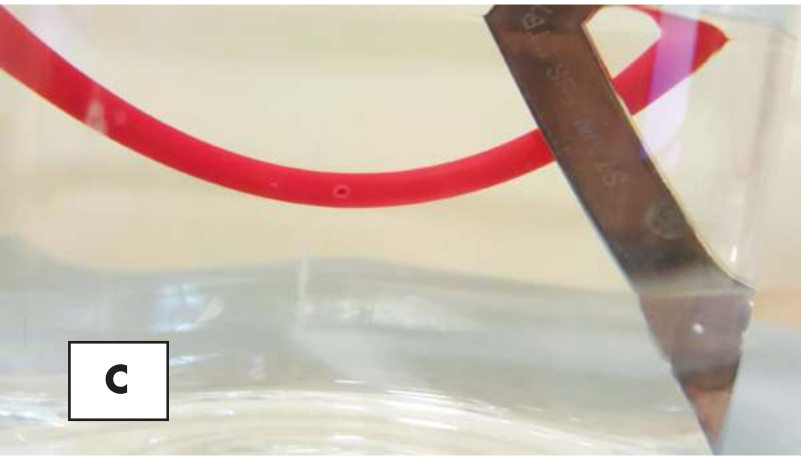
With academic papers arguing that 50 or 60Hz ac power would not result in corrosion of the wire and practical experience suggesting that corrosion could occur, it was decided to set up a series of controlled laboratory experiments to assess the impact on the corrosion of the conductors.

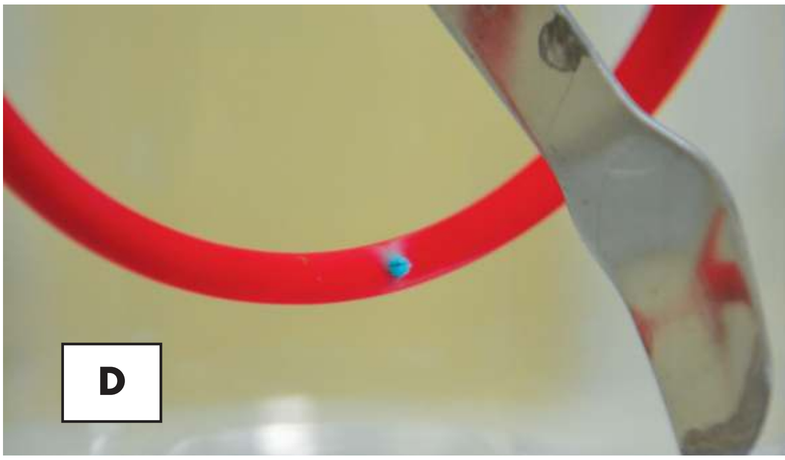
VERIFICATION BY EXPERIMENTATION

A series of experiments were set up to verify whether IMDs did in fact cause corrosion of the copper conductor when a single IR fault occurred. Subsequent experimentation investigated what, if any, corrosion would occur if a 50Hz mains voltage was applied to a seawater submerged cable that had IR faults linking the two conductors via a leakage impedance.

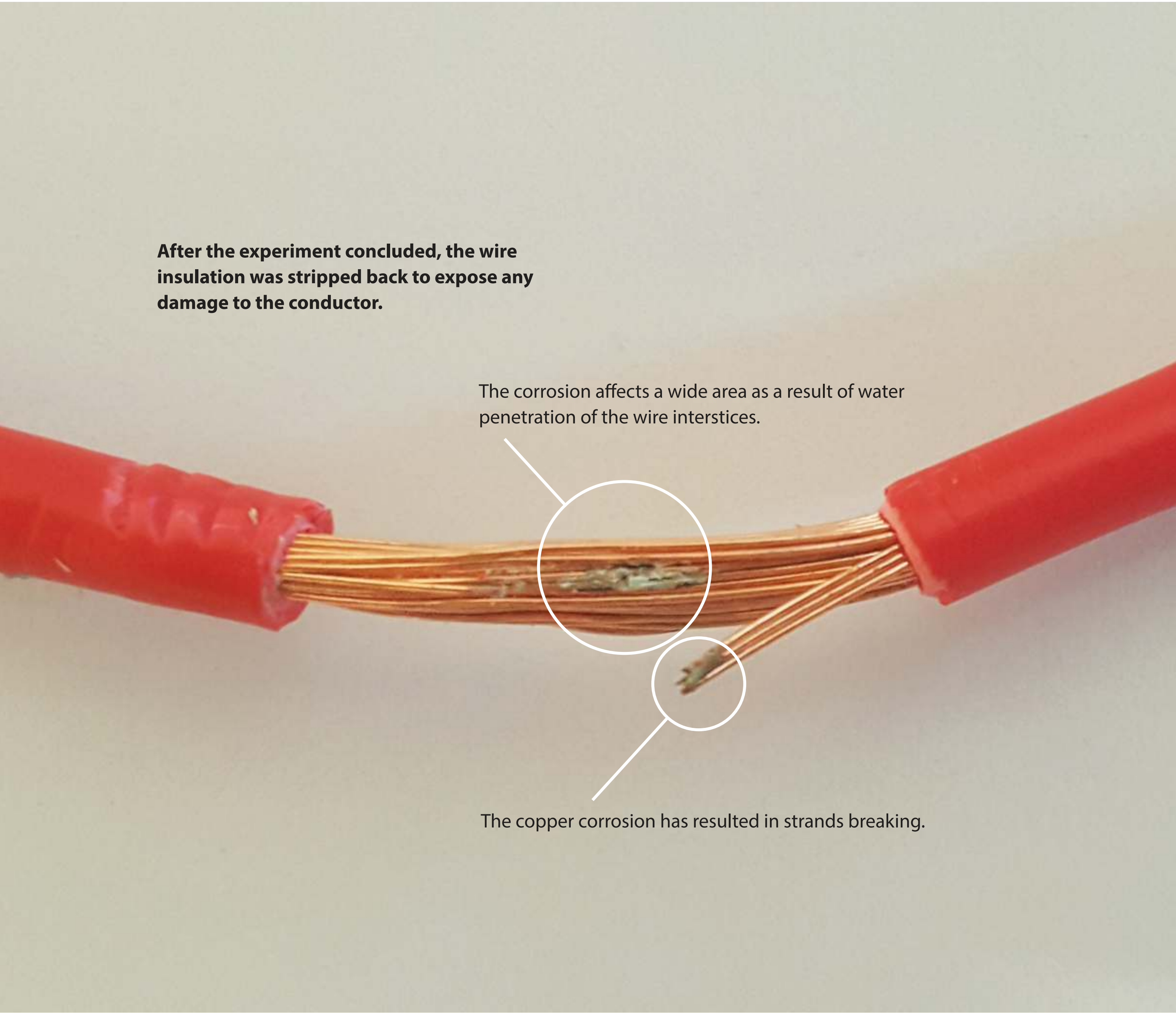
For all experimentation, damage was caused to the cables under test that resulted in an IR reading of circa 30kohms. A fairly low IR was selected for the testing to ensure the corrosion effects were seen over a relatively short test period of two weeks. In the real world, such a low IR level could be as a result of many different failures; ranging from damage to the insulation at a single location (as created in this experimentation), through to multiple, but less severe, points of damage or degradation, through to failure where the insulation becomes permeable and water penetrates along the entire length of the cable.

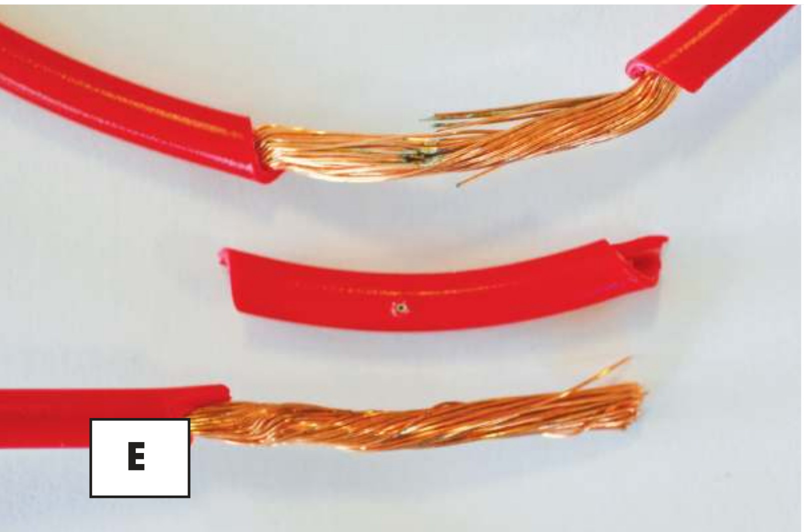
Results of the two-week experimentation can best be summarised with the aid of photographs. Initially an IMD was connected to a damaged wire which was submerged in simulated seawater, and a steel rod was used as the 'earth' conductor, which acts as the return connection to the IMD, in the same way as the platform leg or umbilical wire armour would do in a real situation. The two photo references show the damaged wire at the start of the experiment (C) and the wire after the two weeks (D). What can clearly be seen in the second picture is the copper corrosion deposits leaching out of the damaged cable.

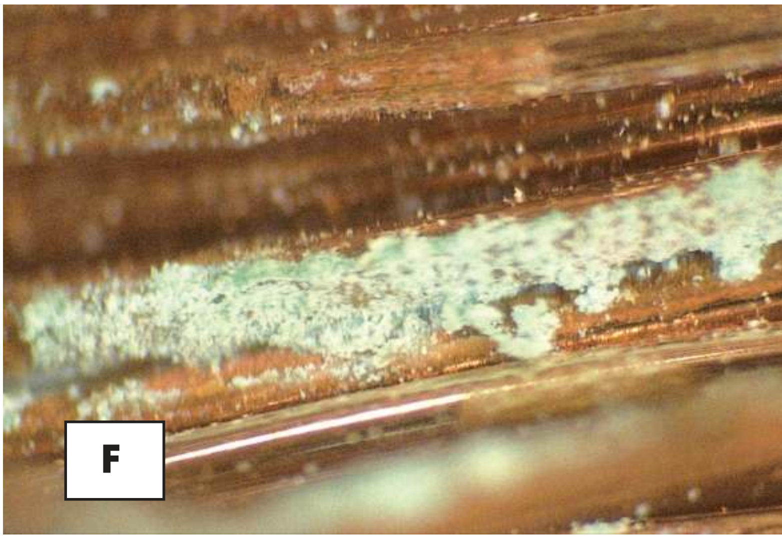




After the experiment concluded, the wire insulation was stripped back to expose any damage to the conductor.





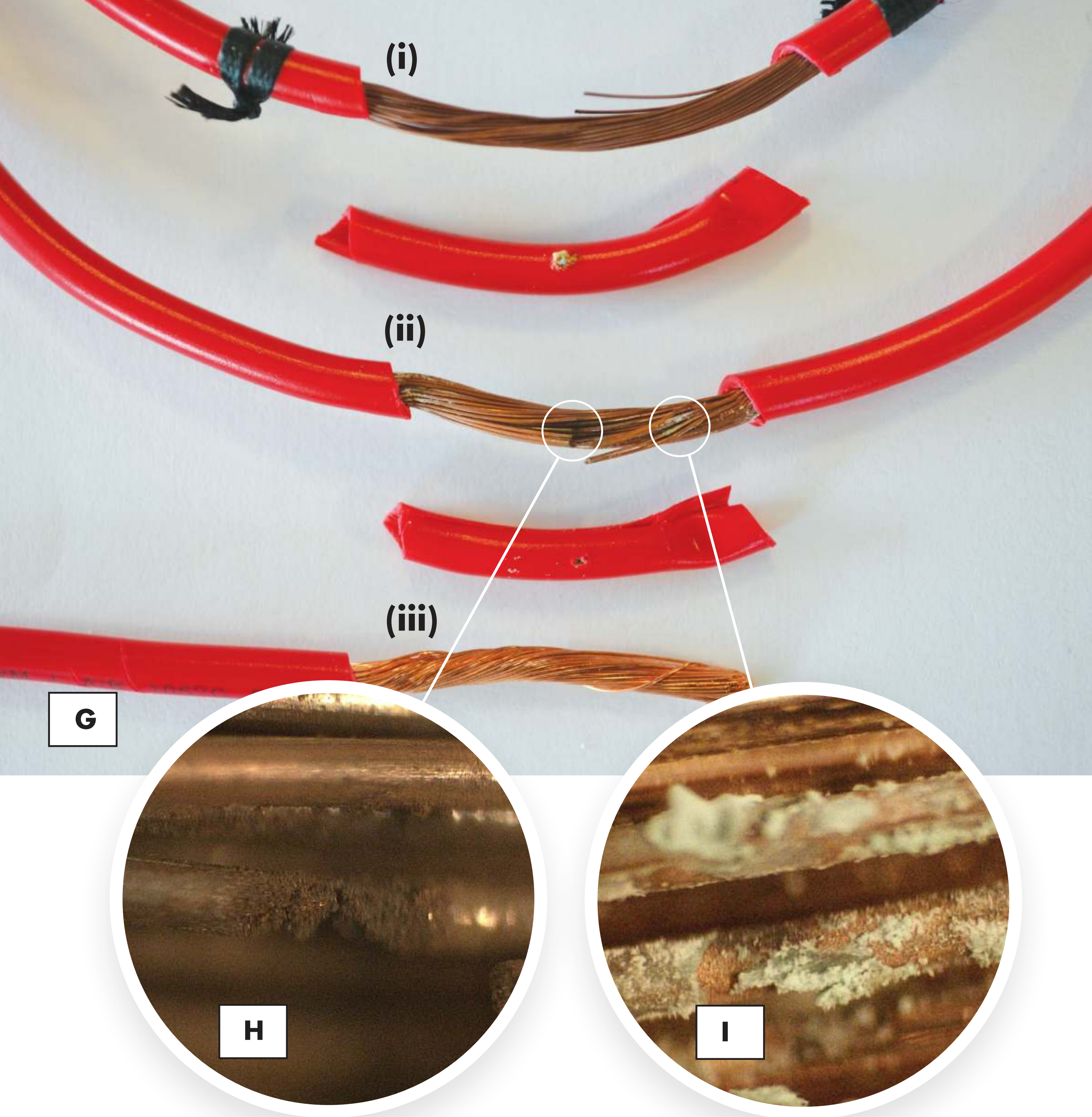


When the cable insulation was stripped away, the blue copper corrosion and green copper corrosion deposit was observed around the immediate area of damage. The image (E) also shows the breaking of copper strands in the cable, where two or three strands are broken. In (E) the top wire is the corroded wire after the two week immersion energized by an IMD and the bottom wire is a length of the virgin wire for comparison purposes. The image in (F), taken via a microscope not only shows the corroding copper (see the strand at the top of the image) but also the green copper corrosion deposit.

Probably of most interest is the result of applying a mains voltage (240V) at 50Hz. When the ac signal was applied, the formation of bubbles at both electrodes was observed relatively quickly, which from theory would be hydrogen gas. The corrosion products leaching from the damaged cables were not as obvious, but when the insulation was stripped back at the end of the two week period, it was apparent that both electrodes (conductors) were badly corroded.

As per the previously quoted equations, it would appear that both conductors corrode since they individually become the anode during one half of the 50Hz applied signal.

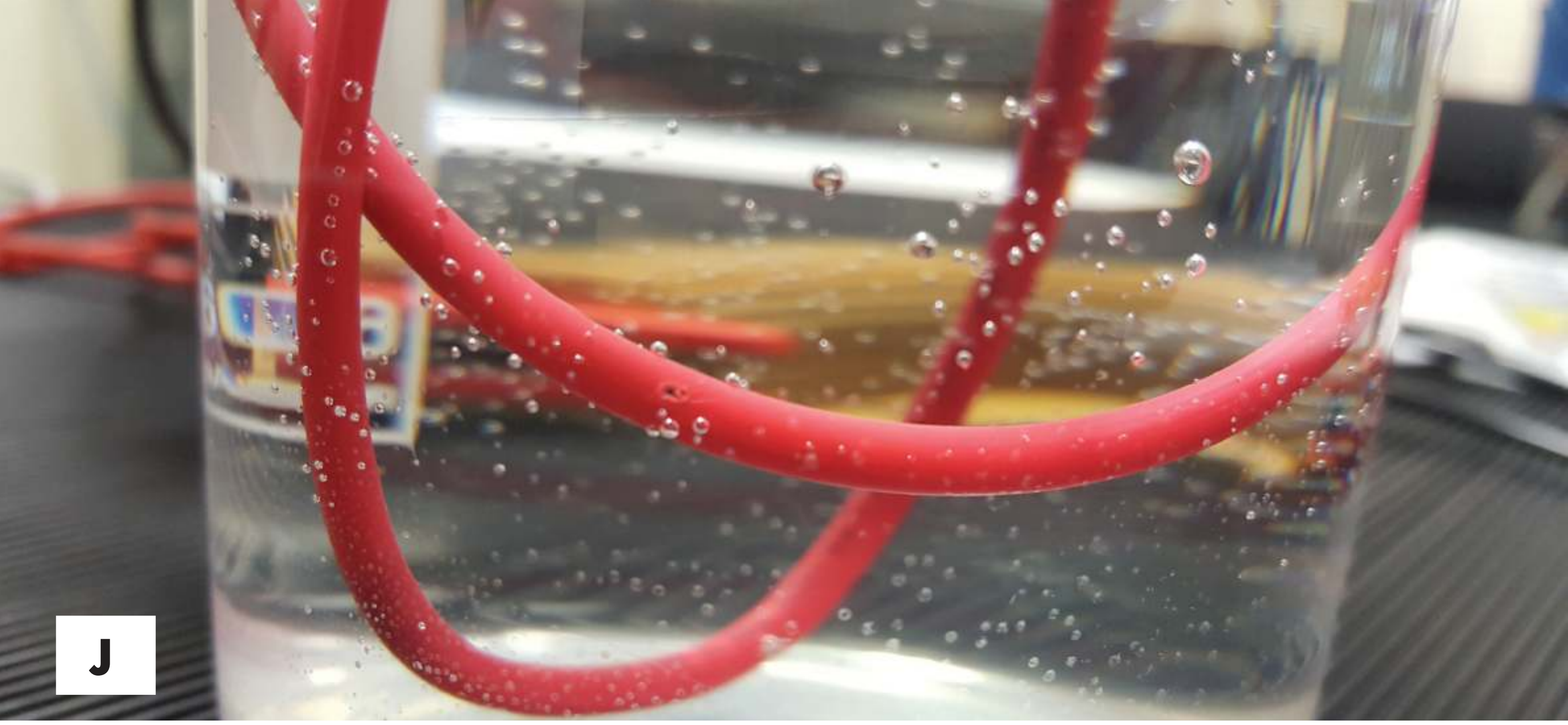
Clearly at the voltage and frequency applied, the electrochemical corrosion process the dissociation and transfer of ions can be sufficiently established within the sinusoidal half cycle of 10 milliseconds to have a detrimental effect on the conductors.



The copper on both wires (G(i) and (ii)) appears severely tarnished compared to the clean virgin copper wire (G(iii)). This indicates that water ingress was not inhibited throughout the experiment, with copper loss occurring throughout the cable and not just at the place of the fault in the insulation.

At least five strands of copper have been affected in one of the wires, where a significant loss of copper has occurred – clearly seen in the optical photo (H). This photo also shows that the copper wires were broken due to the loss of copper in the area.

It should also be noted that when the wires were stripped back and dried, there was evidence of NaCl crystals (shown in photo I), confirming that the salt water had in fact penetrated the wire significantly.



Hydrogen evolution will occur at the cathode with such a high applied voltage, which was confirmed through observation during the experiment. The photo (J) shows the gas bubbles forming around and from both wires.

These experiments have confirmed that with insulation resistance problems on a submerged cable, there will be damage to the copper conductors as a result of connecting an IMD, or if both wires are impaired then simply applying a voltage between the conductors will cause copper loss.

There are two schools of thought as to how to deal with these faults; monitor and leave until failure or replace equipment until the fault or faults are found. What if there were a third option?

One way of reducing the impact of low IR is to deploy Viper's innovative **V-LIFE** technology. **V-LIFE** is a software activated function of the topsides located **V-LIM**, that initiates an electro-kinetic and electrochemical process within the damaged cable. The application of **V-LIFE** blocks any pores in the insulation with a precipitate, thereby removing the seawater electrolyte and increasing insulation resistance. As a result, the leakage current decreases and any copper loss is dramatically reduced. One concern that has been mooted is that the **V-LIFE** process could itself damage the conductors. However, these experiments confirm what we have seen over six years and 80 installations of **V-LIFE**. When the process starts (i.e. from the initial connection), the leakage current and, therefore, the copper loss is no worse than that resulting from a **V-LIM** measurement, which is essentially 30% less loss than a standard system with a competitor's IMD connected. Illustrated below is the leakage current that occurs once **V-LIFE** has increased the IR:

Insulation Resistance	**V-LIM** / **V-LIFE** Leakage Current
30KΩ	120µA
3.5MΩ	45µA
30MΩ	13.3µA

The overall copper loss is directly proportional to the leakage current and so it can be clearly seen from the above that the amount of copper lost from a conductor that is suffering from seawater ingress and is being monitored by a LIM device can be dramatically reduced by the application of **V-LIFE**. In the scenario where there is a fault on both conductors, **V-LIFE** will increase the IR on both thereby also reducing considerably the copper corrosion as a result of the surface to subsea power transfer.

If **V-LIFE** can be used to increase the insulation resistance to 3.5MΩ from an assumed starting point of 30kΩ, then the rate of copper loss will be reduced by a factor of more than four times over the rate of loss due to the standard third-party IMD. If the insulation resistance is increased to 30MΩ, then the factor increases to almost 15 times less copper loss.

One further differentiator of the **V-LIM** when compared to competing IMDs is that in low IR scenarios (typically <100kOhm) the **V-LIM** can indicate the 'balance' of the IR between the two conductors (i.e. determines whether you have a fault on one of the conductors or on both) and therefore whether damage as a result of the supply voltage is likely.

Even with multiple **V-LIFE** restarts, the copper loss is never as high as that which would be experienced by connection of a standard third-party IMD.

IN CONCLUSION

The use of an IMD to monitor IR degradation in a cable which is submerged in seawater will cause damage to the copper conductors at the point where the conductor insulation is damaged.

The Viper **V-LIM** has been designed to reduce the copper loss when compared with competing IMDs on the market. In addition, the Viper **V-LIM** can also be re-configured to reduce the applied voltage and therefore leakage current in low IR conditions – further reducing any copper loss.

Even though copper is lost during the use of an IMD, the loss of copper is significantly greater when there is a line voltage on a copper cable which has suffered from IR degradation on both wires and so operators of subsea fields should recognise that system power applied to an umbilical or cable with low IR will result in corrosion of the copper conductors.

Besides replacing failed cables and umbilicals, the only real solution to mitigate the copper corrosion is to activate **V-LIFE** on the Viper **V-LIM**.

The **V-LIFE** process blocks any paths that the seawater will take to reach the copper and thereby reduce, by orders of magnitude, the corrosion of the copper and subsequently extend the life of the subsea electrical infrastructure.

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