

## THE HISTORY AND SCIENCE OF HYDROGEN IN SUBMARINE NETWORKS

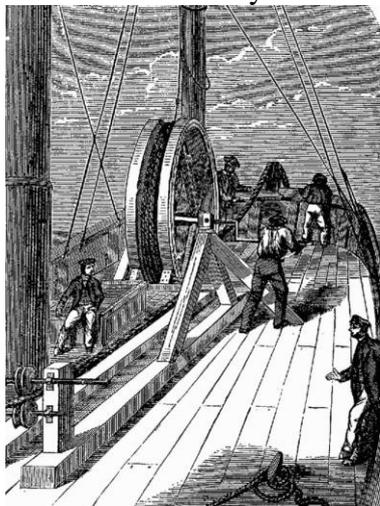
David L Walters, P Worthington (Independent Consultants)  
Email: david.walters@rodbridge.com

The Brambles, Long Melford, Suffolk, CO10 9HQ, UK

**Abstract:** It is an ironic and interesting fact that the performance of the best data communication medium so far developed: optically-amplified fibre, is adversely affected by the presence in molecular form of the most common element in the universe: hydrogen. Molecular hydrogen had been found to accumulate in submarine communication cables ever since their first use in the 19<sup>th</sup> century. The ingress of this hydrogen into submerged housings was the most common cause of premature failure in the electronic analogue repeaters installed in systems from the 1950's until the 1980's. When the first optical networks were being developed it was discovered that the mere presence of molecular hydrogen directly increased the attenuation of fibres. This meant that all cable, joints and submerged equipment needed to be designed in a way that ensured that the levels of hydrogen were managed so that they remained below sufficiently low minima in all key parts of the submarine network. Our understanding of the mechanisms of the generation, ingress and accumulation of molecular hydrogen, and of its effects on fibre and components, has naturally improved with time. This has resulted in evolutions in the designs of housings, cables, joints and couplings, and in selection and qualification of suitable materials, that should ensure that hydrogen does not have an adverse impact on the reliability of modern submarine networks. It will always be necessary, however, for the designers and operators of submarine networks to be aware of the hydrogen-related risks, especially when these networks are used beyond their original design lifetime.

### 1. EARLY CABLES AND EXPERIENCES

The first submarine telegraph cables were laid in the mid-19th century



**Fig. 1 Installation of the First England-France Telegraph Cable in 1851**



**Fig. 2 Searching for a Fault in a Recovered Length of the First Operational Transatlantic Cable in 1868**

The usual cause of problems requiring a cable repair in the 19th century, just as now, was damage caused by external aggression or

abrasion. It is understood that, from even these early years, jets of flame caused by the ignition of high-pressure hydrogen would sometimes emanate on the ship from cables recovered for these repairs. It is not clear from any documented records when this phenomenon was first observed, but it may or may not be significant that none of the shipboard engineers in figure 2 are seen to be smoking!

## **2. ELECTRONIC ANALOGUE REPEATERS**

Apart from being a potential safety hazard during repair, the hydrogen in itself had no adverse effect on the performance of the telegraph cables or on the unrepeated telephone cables which eventually succeeded them in the 20<sup>th</sup> century. This situation changed, however, with the advent of repeated analogue submarine telephone cables in the 1950's.

These first repeated cables used electronic amplifiers with associated power, supervisory and filters contained in cylindrical metal pressure housings quite similar in many respects to those used for today's optical amplifier repeaters.

The polyethylene-insulated electrical cable entered these housings through injection-moulded polyethylene glands. These glands provided a good electrical and pressure-resistance performance, but were certainly not hermetic to hydrogen, so that any molecular hydrogen in the vicinity of the repeater and cable could enter the repeater housing with very little resistance.

The early analogue repeaters used thermionic valves, which were only superseded by transistors in the late-1960's. Several in-service failures occurred both in valves and transistors, and investigation and analysis of these recovered repeaters indicated that in the majority of cases the cause of these premature failures was the chemical reducing

action of molecular hydrogen present within the repeater housing. The actual failure mechanisms: dis-bonding of critical connections, formation of water causing electrical shorting or breakdown etc., varied with different designs, components and materials, but the simple presence of molecular hydrogen was generally seen to be the primary cause of most of these premature failures.

High reliability has always been an essential requirement for submarine cable links, and so after these hydrogen-related risks had been discovered various design changes were made to eliminate, or at least to reduce, the potential long-term hydrogen levels within the repeaters. The main approach was to adopt the use of catalytic 'Hydrogen getters' within the housings which basically oxidised and absorbed hydrogen and so significantly reduced the amount existing within the repeater as free molecules.

There was a general improvement in repeater reliability as a result of these changes, but the presence of hydrogen continued to be the largest single cause of in-service failures in electronically amplified submarine cables.

These analogue repeated submarine cables were, as we are all aware, replaced by optical cable networks from the mid-1980's onwards.

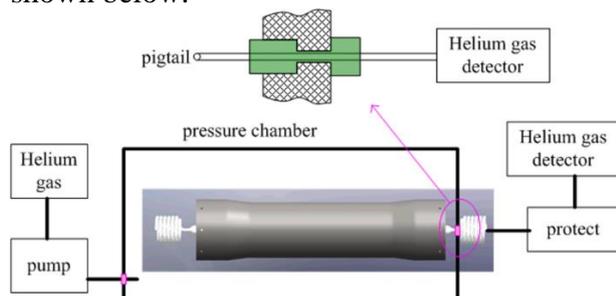
## **3. HYDROGEN HERMETICITY OF OPTICAL REPEATERS**

The opto-electronic regenerating repeaters that replaced the analogue systems contained a very large number of potentially hydrogen-sensitive components and it was realised at the outset of their development that the housings needed to be made as hermetic as possible.

This hermeticity was successfully achieved by all the major manufacturers of submerged equipment using a combination of

metal/metal seals, glass/metal seals, metallised fibre glanding, and polymeric materials with a better resistance to hydrogen than polyethylene (ref. 1).

The gas permeation coefficient of a whole repeater housing can be measured, generally using helium rather than hydrogen for reasons of safety, using an arrangement as shown below.



**Fig. 3 Measurement of the Gas Permeation Coefficient of a Whole Repeater Housing**

The permeation coefficient measured by the technique shown in fig. 3 or some similar method is conveniently expressed in units of mBar.litres/sec/Bar, not strictly in accordance with SI but a very useful practical unit. Published data by all major manufacturers give very similar figures of around 50E-12 for this value.

These very low permeation coefficients mean that even with a very high external pressure of hydrogen the time-constant for the build-up of hydrogen within a typical housing would be of the order of millions of years and the very small amount of hydrogen resulting from this would have no adverse effect on the repeater internals, even without the presence of a hydrogen getter.

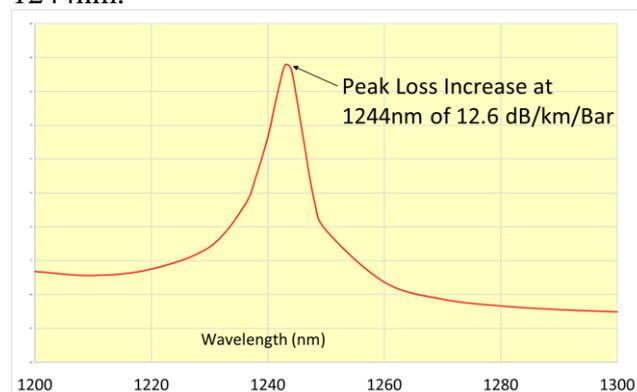
#### 4. EFFECT OF HYDROGEN ON OPTICAL FIBRE ATTENUATION

Despite the entirely successful efforts described in section 3 to make the repeater housings sufficiently hermetic to hydrogen, the original proposed designs of optical submarine cables and joints did not address

the hydrogen-related issues at all, because hydrogen in submarine cable, as opposed to within submerged housings, had never previously posed a reliability problem. It therefore came as a shock when the discovery was made in the early 1980's that the mere presence of molecular hydrogen in the vicinity of optical fibres, at ambient and sea-bottom temperatures, produced a significant increase in optical attenuation at transmission wavelengths (ref 2).

This discovery appears to have been made in three different parts of the world at virtually the same time, and it resulted in a delay of approximately 2 years in the implementation of practical commercial optical submarine cables, to allow time for this new hydrogen-related issue to be addressed.

The main mechanism involved at ambient temperatures and below is not any chemical effect but the simple resonance frequencies of the hydrogen molecule, which are sufficiently close to the optical transmission wavelengths to affect the loss of the fibre when hydrogen molecules permeate into the silica lattice. The following graph shows an actual measurement around the main absorption peak, which is centred on 1244nm.



**Fig. 4 Loss Peak in Optical Fibre at 1Bar Hydrogen Pressure**

Although the loss peak in fig. 4 seems quite sharp at the centre, it has a 'Long tail' which certainly affected the fibre performance at

the first single-mode transmission wavelength of 1310nm.

The hydrogen molecule also has other resonances and harmonics which result in absorption-induced loss increases at the L-band and C-band wavelengths currently utilised in optically-amplified links. The effect is roughly uniform across the C-band with a magnitude of 0.6dB/km/Bar.

## **5. HYDROGEN HERMETICITY OF OPTICAL CABLES AND JOINTS**

The fibres in virtually all optical submarine cable designs are held in some form of central package and this package can be surrounded by a bonded steel or copper barrier which should provide a high resistance to the radial ingress of external hydrogen

However, cable joints and couplings, because of their number and physical size, cannot in practice use the same bonding, sealing and glanding techniques that are used for repeater housings and so their gas hermeticity will always be lower by several orders of magnitude.

The submarine Universal Joint (UJ) that has been developed over many years is the most widely used and a very reliable cable joint. Its specified hermeticity to hydrogen is 9E-7 mBar.Litres/sec/Bar, and measurements and field experience have confirmed that a UJ will meet this figure, but also that the hermeticity achieved should not be expected to be significantly better than that. Comparing this with the figure quoted in section 3 for repeater housings, it can be seen that the gas leak rate into joints and couplings is about 4 orders of magnitude greater than the leak rate into repeater housings. Furthermore, because the internal free volume of a joint is much less than that of a repeater, the internal pressure in the joint will build up more quickly for a given leak rate.

This means that the time-constant for the build-up of hydrogen in a joint is quite close to the nominal system working lifetime of 25 years. It can therefore be appreciated that any hydrogen external to a cable joint or coupling will permeate into the joint to a significant extent during the working life of the cable.

## **6. SOURCES OF HYDROGEN, POTENTIAL AND ACTUAL**

The quantity of hydrogen, in terms of its pressure and volume, which can accumulate in some parts of a submarine network is sometimes a cause of surprise. This high level is explained by the fact that any molecular hydrogen present in the sea at a given depth will be at a partial pressure equal to the local hydrostatic pressure at that depth. Hydrostatic pressure increases by roughly one atmosphere for every 10m increase in water depth so that, for instance, at 1500m water depth the partial pressure of any hydrogen present will be 150 atmospheres. This hydrogen can seep into parts of the cable over time at depth and it will not necessarily flow out immediately as the cable is recovered to the surface, hence the occasional release of very high pressures of hydrogen when a cable is cut.

This explanation accounts for the high pressures sometimes encountered, but the actual sources of the hydrogen still needed to be explained. A number of possibilities were originally put forward, which can be summarised and commented upon as follows.

- Emanating into the seabed from the crust of the earth.

While geophysics indicated that this could theoretically be a possible source, the practical field evidence, particularly the fact that armoured cables in shallow water generally exhibit far higher levels of hydrogen than those encountered in deep-water cables, ruled this out as a significant source.

- Decaying organic matter on the seabed.

A small amount of hydrogen can be produced by this mechanism, though the main products are hydrocarbons and CO<sub>2</sub>. But practical experience has shown that this source too is not a significant factor in affecting the hydrogen levels in submerged plant.

- Long-term decomposition of repeater and cable materials.

Laboratory tests and some field experience have shown that this is certainly a factor that needs to be taken into account. Hydrogen outgassing measurements need to be carried out at elevated temperatures as part of the qualification of any materials to be used in cables or submerged plant, to ensure their stability over the system lifetime and to ensure that getters inside the repeater housings are adequate to cope with any hydrogen evolved. But provided those qualification procedures are followed, this source should not impact upon network reliability and lifetime.

- Metal corrosion and MHD effects.

These related electrochemical effects have been found over many years to be the most common and the main potential source of hydrogen in cable and submerged equipment. Details of the various mechanisms involved are described in the next sections.

## 7. CORROSION OF ARMoured JOINT HOUSINGS

Cable armour wires and armoured joint casings are invariably steel, and this will always oxidise to some degree in sea water by the simple reaction:



This corrosion reaction will be much more significant for the joint casings than for the armour wires because the armour wires are generally better protected from the sea water by coating and roving than any joint casing could be in the long term. It is also true of

course that, since joints and couplings are by a large margin the least hermetic part of the submerged network, hydrogen generated in their vicinity will potentially have a much greater effect than hydrogen which may be present at other external points.

The degree of corrosion that actually occurs at a joint will depend on a range of factors such as temperature, sea-bottom conditions and salinity etc., but some published data (ref. 3) has indicated a rough worst-case corrosion rate for mild steel totally immersed in sea water at ambient temperature (~15° to 20°) of about 1800gm/m<sup>2</sup>/year. At typical sea-bottom temperatures the worst-case corrosion rate would be somewhat less than half of that, say at around 800gm/m<sup>2</sup>/year.

The amount of molecular hydrogen corresponding to this metal corrosion is calculated to be around 150mBar.litres (or 130cc at NTP) of molecular hydrogen per day for an armoured UJ casing. The vast majority of this hydrogen will dissipate harmlessly into the sea or sediment, but a small quantity can be expected to penetrate into the joint.

The results of a 400-day trial, in which hydrogen build-up was monitored in an armoured UJ in 150m sea-water depth, were reported in a paper at SubOptic 2016 (ref.4), and these results were consistent with the corrosion rate described above. If the average build-up rate reported in ref.4 were to continue indefinitely, it would result in a hydrogen pressure within the joint of 3.2Bar after 25 years in service.

Using a figure of 2m for the total length of fibre in a single path though a UJ, that pressure of 3.2Bar after 25 years would result in a C-band loss increase of 3E-3dB for the fibre in the joint. That is an order of magnitude less than the loss of a typical single-mode splice, so it should not be regarded as significant and would certainly not have any effect on system margins.

However, if this hydrogen were to migrate from the joint into the cable, so that a longer length of fibre became subjected to the same significant pressure of hydrogen, then the hydrogen-induced loss would increase pro rata. This was seen to happen in some early designs of optical cable, but the central fibre package in modern cable designs should now be sufficiently well blocked for this axial hydrogen penetration not to be an issue for current and future working cables.

Natural corrosion of joint housings should not therefore be a system-threatening problem for modern submarine networks. The risk increases, however, if the electrochemical effect is enhanced by additional factors, as discussed next.

## **8. EXACERBATION BY THE EFFECT OF MHD CURRENTS**

MHD (magneto-hydrodynamic) effects, also known as the Hall effect, arise when a conducting medium such as sea water moves in a path perpendicular to a magnetic field, such as the vertical component of the magnetic field of the earth.

An ocean current flowing with a velocity  $V$  m/s perpendicular to a vertical magnetic field of magnitude  $B$  Tesla will result in an electric field of magnitude  $E$  volts/m which is the vector cross-product of  $V$  and  $B$ :

$$E = V \times B$$

Because of the voltage difference produced by this induced electric field, a current will flow in the cable armour wires. At any point where the electrical resistance of these armour wires changes, and especially of course where they are completely terminated, some or all of this electric current will flow into the sea, resulting in metal corrosion at a positive end and hydrogen generation at a negative end.

At a typical value for  $B$  of 40 micro-tesla, an ocean current of 1m/S would result in an electric field of 40mV/km. This in turn would produce a direct current of 80mA in typical cable armour wires. If all of this electric current flowed into the sea at one location, it would produce around 830 mBar.litres/day of hydrogen: an order of magnitude more than would be likely to occur from natural corrosion of a joint housing. The figures for magnetic field and ocean current quoted above are typical, and ocean currents in particular can sometimes be higher. There has been at least one instance when this electrochemical effect led to a failure requiring a marine repair after only a few years in service (ref. 5).

At the relatively high hydrogen-generation rates that can sometimes be produced by this phenomenon, the local partial pressure of the hydrogen will probably be limited only by the hydrostatic pressure. This means that the hydrogen pressure inside an armoured joint or coupling experiencing that external hydrogen pressure will build up over the system lifetime to a much higher level than the ~3bar quoted in section 7. Depending on the depth and other factors, a pressure of over 100Bar may well be possible.

This phenomenon may still not be system-threatening: a hydrogen pressure of 100Bar contained within a joint would only result in an increase in C-band loss of 0.12dB. So, provided that the part of the cable containing the fibres is sufficiently well gas-blocked, there would be no impairment to system performance.

## **9. BRANCHING UNIT SEA-EARTHS**

Branching-unit earths, at which the line current is fed directly into the sea, are almost always cathodic to avoid possible corrosion problems, and a 1amp line current would result in the production of 10,000 mBar.litres of hydrogen per day at the electrode: more than an order of magnitude higher than

would normally be produced by any natural mechanism, even with MHD currents.

Problems resulting from these earths have sometimes required marine repairs in the past, so the latest designs now ensure that the electrodes are always sufficiently far from any non-hermetic parts of the system, to avoid any hydrogen-related problems (ref. 6).

## **10. WORKING LIFETIMES OF CURRENT AND FUTURE SUBMARINE NETWORKS**

Submarine networks have traditionally had a design lifetime of 25 years, though before the advent of optical amplification most systems were taken out of service in less time than that because they were superseded by improved technology. However, the multiple upgrades that are now possible mean that all of the submerged part of the network may ideally be required to work well beyond 25 years if possible.

Provided that all internal repeater and cable materials are qualified to assure their long-term chemical stability, there would seem to be no reason to believe that any hydrogen-related phenomenon would impact adversely on extending the lifetime of any part of the submerged network, with the possible exception of armoured cable and joints.

As described in section 8, MHD-enhanced electrolytic corrosion can cause hydrogen pressure in armoured joints and couplings to rise to the local hydrostatic pressure. This is not a problem unless that hydrogen then permeates axially along the cabled fibre to a significant extent. Measurement of the resistance of cable core to high-pressure axial gas permeation would quantify and scope this possible risk.

With that proviso, there appears to be no reason to believe that any hydrogen-related phenomenon would impact on the extension

of the working lifetime of modern submarine networks.

## **11. REFERENCES**

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