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Analysis of the half-life 'ageing-constant' theory for galvanic anodes: Analysing the model's predictive power for CPT anodes.

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Abstract. Over the last 4 years, an empirical model describing the current from galvanic anodes has been released based on limited data from some galvanic anodes. The model describes how the current from these anodes appears to halve over set time intervals. This 'ageing constant' has been used to design anode systems based on a minimum current requirement for protection and broadly applied to other galvanic anode systems. This is a radical change from the responsive behaviour model of corrosion management typically applied to galvanic anodes where the effect of the anodes was more typically tested using methods such as visual inspection, steel potentials and steel corrosion rates. In this work, we will break down the hypotheses behind this model; from the minimum current threshold being the same for all galvanic anode systems, ignoring the current spread from different anode placements, and the predictive power of this model, using data from a system cited by these authors from a Concrete Preservation Technologies Ltd (CPT) hybrid anode system. The authors of the half-life model utilised the first 7 years of data to generate an ageing constant. Now, with over 17 years of data, the model will be assessed and dramatically different conclusions drawn on the effectiveness of this model for predicting the life of CPT anodes.

1 Introduction

In November 2020 (online, 2021 in print), Sergi et al. published 'Monitoring results of galvanic anodes in steel reinforced concrete over 20 years' in Construction and Building Materials [1], first coining the term 'ageing-constant' or 'ageing factor', for galvanic anodes. The authors sometimes refer to this empirical model as the 'half-life principle' [2]. The general premise of their hypothesis is that galvanic anodes have a reduction in current by half over set time intervals, ultimately trending to zero. The argument follows that when said current falls below a set value, the system no longer adequately protects the reinforcement.

Their data in this initial work appears to be limited to 12 patch anodes from 1 site. The analysis discusses how the anodes appear to go through three stages of relatively constant current output and the half-life ageing constant is generated by the plotting of the approximately 30 current readings over 21 years on a logarithmic scale and a straight line being fit to the data [1]. The arguments for why this may occur were limited to measurements regarding decreases in anode surface area and depletion of lithium hydroxide which was likely used as the activator for these anodes.

This idea was then built upon in 2021 in the Journal of Building Engineering (June 2021) [3], at the Corrosion Conference (November 2021) [4], Structural Faults and Repair Conference (2022), in the book Life-Cycle of Structures and Infrastructure Systems [5], and 3rd Conference & Expo Genoa (2024) [6]. During this time, the 'ageing constants' were published for 12 elements using Vector Corrosion Technologies (VCT) anodes or their precursors, as well as lab and other data from their product range. In the AMPP Italy Corrosion Conference white paper, the half-life hypothesis was directly applied to other companies' products and an 'ageing constant' was published for a CPT DuoGuard™ anode system [6].

What is of note in this development is CPT anode systems are cast with a different geometry, embedded in a different cementitious material, located in the host concrete rather than a patch, and the data used was from anodes activated with halides, that are drawn to the anode surface through their use, an activator type that is not depleted in the same way during the life of the anodes. Therefore the original theoretical underpinnings of the original work would be thought not to apply and a new explanation for these anode types was created, the accumulation of zinc corrosion products around the anodes [6].

This ageing constant was created using anodic current data from the first nine years of the galvanic protection of Whiteadder Bridge in the northeast of England, published by CPT [7]. The claim in the AMPP Italy white paper was that this system has a 2.9-year 'ageing constant' and, therefore, is likely to have a relatively short life [6]. No graph or image of the data that was used in the calculation of this number was found during a review of the literature.

Whiteadder Bridge has been monitored for over 17 years, with over 100,000 data points collected, including current output and steel potentials. Therefore the predictive power of this model can be tested using data from a site used in their analysis using data we may presume they had little access to. We believe this is the first test of this model's predictive power despite its current use in specifications and design documents worldwide.

1.1 Aim of this work:

The half-life or ageing factor put forward by VCT *(AMPP 2021)* can be simply stated in three points:

- There is a set minimum required current for the protection of steel in concrete that is the same for all anode types, similar to that mentioned in ISO 12696 [8].
- The current from all galvanic anodes decreases by half during a set interval (a half-life) and continues in this trend to the end of its serviceable life.
- Anodes respond to changes in temperature.

Here we will break down the first of these hypotheses and put forward an argument against a minimum required current output using the principles of current spread and mixed potential theory, a fundamental of corrosion science. In the case of the half-life hypothesis, data from the DuoGuard™ system at Whiteadder Bridge will be plotted alongside the empirical model's predicted values and a simple constant current null hypothesis.

2 A theoretical deconstruction of the minimum current requirement.

One of the reasons that current data from galvanic anodes is not common in literature is due to the current provided by these anodes being responsive to changes in moisture, temperature and changes in ionic composition which cause the zinc to corrode at differing rates [9]. Therefore the current measurement may vary depending on the environmental conditions during the test. Monitoring, when applied, is more often in the form of reference electrodes or half-cells being applied to either the surface of the concrete or installed within the concrete which can track the polarised potentials [10], and if the system is wired in such a way, the natural steel potentials [11].

The first and most fundamental point that must be made when looking at the current requirement is the question of where the current is flowing. Current will flow following two general principles; between areas with high driving voltages and via paths of minimal impedance. Therefore, the current is more likely to flow to steel close to the anodes with lower impedance and, due to higher driving voltages, to areas that are not corroding (are cathodic) [12]. Below is a graph showing data taken from [13] overlayed with lines indicating the anodic reaction of high corrosion-risk steel (lower red line) and low corrosion-risk steel (upper red line) and their intersection with the cathodic reaction (blue). Where these lines intersect gives you the corrosion potential and the corrosion rate of this steel. This is a basic principle of Mixed Potential Theory.

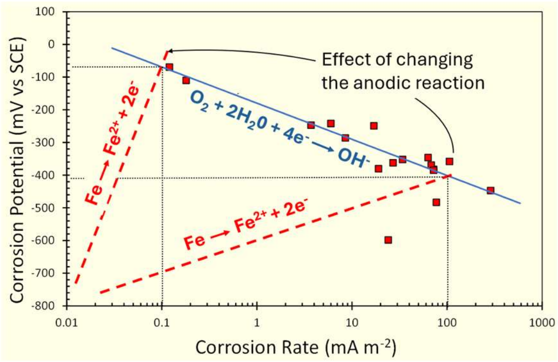

Fig. 1. Graph using data from Corrosion 1997 work [10] showing steel in an oxygen-rich environment falls along a (downward sloping) line that describes the cathodic reaction of steel. The anodic and cathodic reaction lines intersect at a high corrosion rate with a more negative steel potential, and a corresponding low corrosion risk, at less negative steel potentials. The driving voltage between these steel surfaces is displayed indicating the corrosion cell that would form if these sites were electrically continuous in the presence of an electrolyte such as concrete.

As can be seen, the high corrosion risk steel has a substantially higher corrosion rate and a more negative steel potential. This fits well with the general understanding of steel potentials used to survey sound at-risk concrete. Due to the potential difference between these two steel locations, if these two areas of steel were to be connected electrically and ionically a corrosion cell would form between these two areas of steel corroding the more negative steel potential reinforcement and cathodically protecting the less negative steel. This also fits the common wisdom of the industry and is the basis for macrocell corrosion.

Furthermore, the amount of current required to polarise the steel by a set amount will depend on the slope of the anodic curve and the corresponding unprotected corrosion potential and corrosion rate. This can be seen clearly in the graph and summarised in the table below [12] where more negative steel potentials and higher corrosion rates require much larger currents to provide the same level of polarisation. Therefore, the corrosion risk of the steel cannot be determined purely by the current supplied, nor the amount of polarisation but by their relationship which can give us a greater understanding of the corrosion rate of the steel being protected.

Table. 1. Graphically calculated table showing the relative polarizability of steel at various corrosion rates,. Extracted from [12]

Corrosion rate (mA/m^2)	Current required to polarise steel by 80 mV (mA/m^2) (graphically calculated)
0.1	0.54
1.0	5.5
10	57
100	590

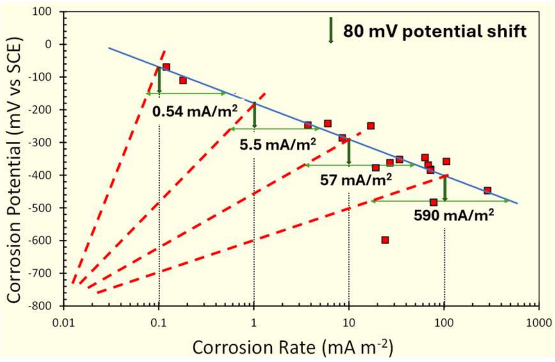

Fig. 2. An image showing that the potential and the corrosion rate in this data can be used to estimate the polarizability of these steel surfaces. This was found to have a good match with lab-based data [12].

A lesser-known consequence of this difference in potential is that the driving voltage between any corrosion management anode and steel will be greater for cathodic steel than the more negative anodic steel. Therefore, all other factors being equal, the current will be driven more strongly to steel that is not corroding.

In practice, this may not be a big problem as the most important effect of cathodic protection, both galvanic and Impressed Current Cathodic Protection (ICCP) is to not provide a given polarisation of the steel, but rather to affect the environment of the steel by drawing away chloride ions which are repelled by the electrons provided to the steel by the applied anodes and the generation of alkaline hydroxide ions at the steel surface that migrate and diffuse to the more anodic areas aiding in their passivation [12]. This is called passivation by realkalisation and results in protected, natural steel potentials becoming less negative over time and requiring less protection.

This is why the best way of understanding the performance of these anodes is not based on a single measurement such as the current or the polarisation but the trend in the corrosion rates and the steel potentials towards passive corrosion potentials (ATSM C876 [11]) and corrosion rates as defined by BRE Digest 444 [14] and the Concrete Society TR60 [15].

2.1 Anode Location

To dive deeper into the claims we must compare the anodes used by VCT in the creation of their model which were precast patch anodes with the most common CPT patch anodes, PatchGuard™. These anodes are designed to provide current to the steel outside the patch to overcome the incipient anode effect, or ring anode effect as it is sometimes known, where corrosion of the steel surrounding a patch accelerates after a patch repair is made [16].

First, let us now look at the relative locations of two anode types, precast anodes similar to VCTs (our own precast anodes have been used in the image for copyright reasons) and CPTs PatchGuard™ anodes. Precast anodes are tied to the steel within a patch whereas PatchGuard™ anodes are located between the steel in the periphery of a patch, a different methodology for protection.

Fig. 2. Precast anode, indicating the anode's relative location in the patch.

Fig. 3. PatchGuard™ anode, image showing the anode's relative location in the patch.

Now the question becomes, where will the current flow? We require it to flow to the vulnerable steel outside of the patch in the host concrete, however, the precast anodes are applied within the patch, tied directly to low-risk steel in a fresh, highly alkaline repair material. Given the alkalinity of the repair mortar used in the patch and the ongoing protection of the anodes, the driving voltage to the steel in the patch will likely be greater. Therefore, current can be expected to flow disproportionately to the steel with the lowest resistance path with the highest driving voltage, directly to the steel onto which it is tied. Much of the current and hydroxide ions created by the flow of electrons will also be generated within the patch rather than in the vulnerable host concrete.

PatchGuard™ anodes are situated between the reinforcement in the host concrete, rather than adjacent to a single rebar within the patch. Unlike their precast counterparts (such as the VCT anodes used in their work [1]), the majority of the current would be expected to flow to the steel in the host concrete. Furthermore, as the anodes are located further away from any single rebar, the relative resistance of the pathways to the

surrounding steel reinforcement will be much less varied than the anodes installed adjacent to a single piece of reinforcement, onto which the majority of the anode's current may flow. The current from the anodes therefore likely to spread more evenly to the steel.
Methodological differences will also play a role in their performance. PatchGuard™ anodes are often used alongside more resistive repair materials, which may have their use limited when applying precast anodes, as the anodes are installed within the host concrete, not the patch.

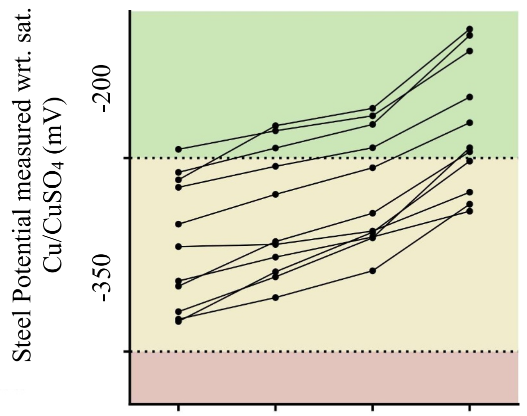

Fig. 4. Depolarised steel potentials taken over 4 years indicating the passivating effects of purely galvanic anode systems

Unlike VCT's precast anodes therefore a high resistivity patch repair material will only aid the anode's ability to push current into the host concrete and promote a larger portion of the current to the at-risk steel. Therefore, little current is wasted (by flowing into the fresh, alkaline patch) and the majority of the protection, and associated hydroxide ions generated at the steel, will be generated in the vulnerable host concrete. The effect of these hydroxide ions is evidenced by the unprotected corrosion potential of steel (sometimes over 1m) away from these anodes becoming more passive over time, Fig 4.

Given the differing efficiency at which these anodes may provide current to the steel in need of protection, is it not strange to think there will be a similar current requirement for both these anode types? Furthermore, the amount of current required to polarise steel depends on its passivity [12]. Therefore, anodes which have generated much more hydroxide around the vulnerable steel may require less current to protect more steel in the more alkaline environment as it will be much more naturally passive.

Together this leads to an intuitive conclusion. The amount of current required to adequately protect steel in concrete depends on the corrosion risk of the steel, its environment, and the efficiency of the anodes in providing a risk-responsive current to the steel. Passive steel in a dry environment is likely to require little protection whereas steel in a wet and aggressive environment with its passive layer interrupted will require a higher current output. The appraisal of galvanic anodes should therefore include their ability to respond to these threats and their effect on the passivity of the steel over time.

3 Responsive behaviour

Galvanic anodes are attached to the steel in concrete forming a cell with the zinc as the anode and the steel as the cathode. The current supplied by the anodes may be reduced by the many resistances in the circuit such as the build-up of resistive corrosion products and the resistivity of the concrete or by the amount or type of activator used, which may act in a limiting capacity [1].

VCT correctly point out the reactive behaviour of galvanic anodes when subject to temperature changes [5]. In fact, this can be seen in the behaviour of CPT anodes and is an integral part of the anode's ability to react to changes in the corrosion risk of structures. Below we can see data from CPT anodes that have behaviour similar to what is described.

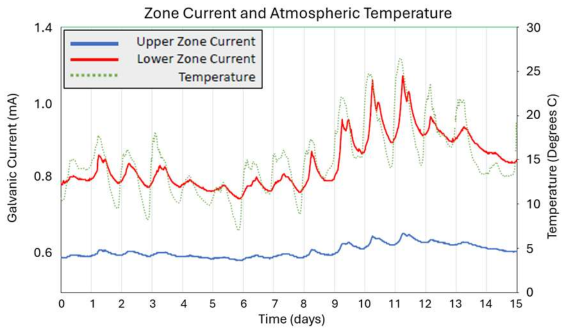

Fig. 5. Graph showing anode current response to temperature fluctuations 9 years after installation.

However, what was not stated was the potentially much greater significance of moisture in the activity of some galvanic anode systems with times of rainfall and flooding showing much more significant increases in current output due to the decrease in resistance of the concrete, which acts as the electrolyte in our cell.

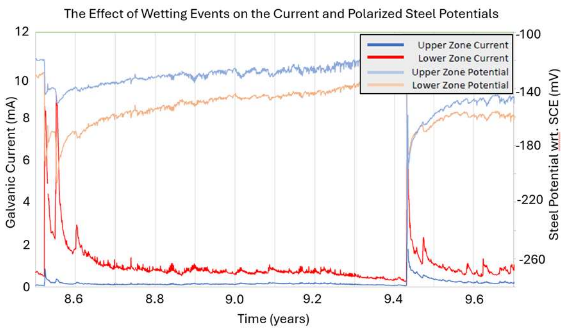

Fig. 6. Anode current and potential data over two zones responding to changes in moisture due to flooding (8.5 years) and rainfall (9.4 years).

These increases in current output can be an order of magnitude or more, giving current densities similar to ICCP systems during these wet events to protect the steel and maintain its passivity. The responsive behaviour of these anodes is one of the keys to maintaining steel passivity in a structure, preventing anodic areas from initiating in the surrounding steel during exposure to moisture

4 Testing the predictive power of the half-life hypothesis

Half-lives are found in radioactive decay due to the random nature of the timing of their decay, decreasing the amount of a radioactive isotope over time. There is no scientific justification for the repurposing of this particular model for anodes, just an empirical analysis that does not test the predictive power of this novel claim.

This is not to say that there is no mechanism for some anodes behaving in such a way either due to an environment drying over time or due to mechanisms particular to an anode's geometry, embedding material or electrochemistry but applying this model to all galvanic anodes requires a burden of proof that I do not believe has yet been met.

To test these claims for CPT anode products, we will analyse the data used by Sergi et al to calculate their published 2.9-year aging constant, Whiteadder Bridge. However, rather than picking an unknown number of data points from the first 9 years of data, we will initially plot the roughly 100,000 data points collected over the first 17 years of protection from the same zone believed to be used by the authors, the most current available dataset.

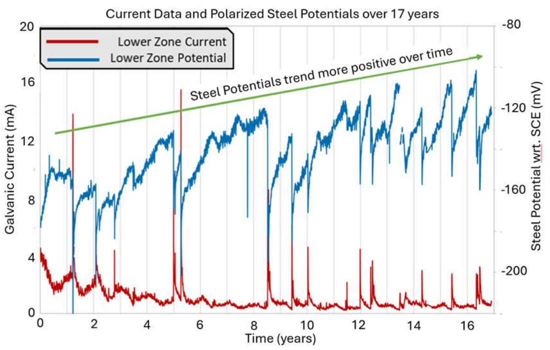

Fig. 7: 17 years of current and polarised (ON?) steel potential data from the zone at WhiteAdder Bridge from which the 2.9 year ageing constant was calculated. A green line was added to show the increasing trend in the steel potential over time.

This system is a DuoGuard™ installation in the UK which was impressed for the first week of life at a high driving voltage and then connected galvanically [7, 9]. For the past 18 years, the system has been powered by the potential difference between the zinc and the steel. Interestingly, this would fit an additional hypothesis by Sergi et al published in the AMPP white paper that states that anodes that are driven hard at the beginning of their life have a shorter ageing constant [6].

In this graph, the red line is the galvanic current from a zone of DuoGuard™ anodes and the blue the corresponding zone's polarised steel potential (i.e. a mixed potential that includes the influence of the current on the steel potentials giving negative peaks during periods of increased polarisation and current flow). The current does indeed decline over the first 6.5 years. This is understood to be due to the system reaching an equilibrium with the concrete and the putty into which the anodes are installed curing. During this time the natural steel potentials rise to more passive, low-risk steel potentials [11] which is part of the intended behaviour of the system. The system is expected to maintain this passivity during the system design life, responding to ongoing corrosion threats that include rainfall, flooding, ingress of de-icing salts and increased temperature.

Now, let us focus on the current from year 8 onwards, overlapping a single year with the data purportedly used by the authors in the calculation of their 'ageing constant'. For the sake of equivalence, we have plotted this current on a logarithmic scale similar to the method the authors use in their analysis. If the proposed half-life hypothesis is correct, we expect the current to decrease by half over set intervals. The white paper helpfully provides a figure of 2.9 years from the first 9 years of this data [6]. This figure can be tested by applying the current value at 8 years and extrapolating the predicted values for the next 9 years using their hypothesised model. What we would expect from the model is a current on a downward trend following an exponential decay. The prediction would therefore be that the current should undergo a little over 3 ageing constants and drop over this period to approximately 11.6% of the 8-year figure.

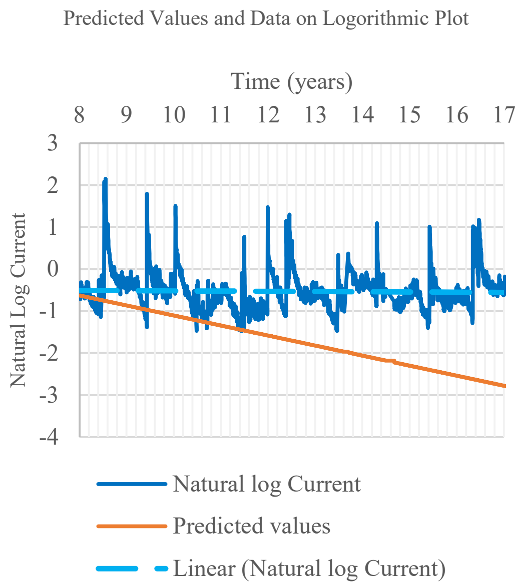

Fig. 8. Natural log of Current plotted over time against the predicted values from the ageing constant hypothesis (red) and a line of best fit (blue dash)

Figure 9 clearly shows the current supplied by these galvanic anodes is responsive by nature as discussed in this work. Therefore, as expected, there are many peaks which correspond to times of high rainfall, flooding and yearly cycles of temperature variation. Sergi's half-life model is not suited to predict the responsive behaviour, but rather, the overall trend in the data. However, the current trend does not appear to conform with the predictive model, diverging ever more strongly from the predicted values over time.

Using average yearly current data, we can reduce the impact of the temperature and moisture peaks and measure the mean squared error (MSE) of Sergi et al's predictive model and a simple null hypothesis, a constant current model, for the sake of comparison against the general trend of the data. The calculated mean squared error (MSE) for the Sergi et al model is found to be 0.237 mA^2, whereas the MSE of a simple constant value model is a mere 0.0135 mA^2. It is reasonable to conclude that the 2.9-year 'ageing constant' fails to predict the long-term current trend of this anode type better than a simple model predicting no change in the current. We must therefore reject the 2.9-year 'ageing constant' as a poor predictor of the current trend.

This alone is not yet sufficient proof that these anodes do not have long-term half-life behaviour, just that the figure of 2.9 years is not a good fit for the behaviour of the anodes. From analysis of the author's work, it appears that the 'ageing constant' was determined by fitting a straight line of best fit to the natural logarithm of the current plotted against time [1, 6]. A half-life 'ageing constant' can be calculated using this simple approach by fitting a linear best-fit line to the log current output data for the 9 years from years 8-17 (blue dashed line in Figure 9). The resulting 'ageing constant' calculated for this data is approximately 36000 years.

This is a severe divergence in the ageing constants calculated from the first 9 years of data and the data from years 8 through 17 of four orders of magnitude. This indicates at the very least a substantial issue relying on initial performance data aging constants to predict the long-term performance of some manufacturer's galvanic anodes. This may be partly due to the nature of the anode's embedding putty which will slowly cure post-installation, inflating the initial current and warping the 'ageing constant' calculated using just the first 9 years of data.

However, the second 'ageing constant' value, calculated using data after the curing of the putty, raises further concerns. it is absurd to predict that sacrificial anodes, with a design life typically between 15-35 years. could have a potential service life that would exceed the life of the oldest known human structure, and be able to produce a current over time far beyond the capacity of the mass of zinc present, which is currently depleted by an average of 6.9% after 17 years. This figure is calculated using lab-based efficiency data for this type of anode and current data for the zone taken at 3-hour intervals.

5 Conclusion.

The idea of a set minimum current for protection regardless of the passivity of the steel, the placement of the anode and other factors involved in the electrochemical protection of steel in concrete is very questionable. We propose that the common wisdom holds and the level of protection achieved by galvanic anodes may be better determined by their ability to progress the steel into a lower-risk state while responding appropriately to corrosion threats such as moisture and temperature. This can be done by monitoring the natural steel potential of the reinforcement and where possible calculating the corrosion rate of the steel using depolarisation or LPR methodologies.

The half-life hypothesis may have ample data from the author's anode systems to potentially be used for their designs. However, given the model's failure to predict data from Whiteadder Bridge, it may be advisable to not apply this model broadly to other anode systems produced using distinctly differing electrochemistry and geometry, and installed with a vastly different methodology. The theory that this drop is caused by a depletion in the activating chemicals used by VCT anodes may have merit and lead to the difference in performance between these systems. This comparison between systems with differing activation types likely has some merit as traditional zinc mass calculations may be misleading for anodes which are purely alkali-activated as the limiting factor in their performance may be the concrentration of hydroxide ions rather than the mass of zinc [1].

The half-life ageing constant model failed to predict the current output of CPT anodes better than a constant current null hypothesis, the current generated by CPTs DuoGuard™ anodes was around 800% higher than predicted by extrapolating their proposed model. The calculated 'ageing constants' were highly inconsistent for these anode types, separated by four orders of magnitude when measured over different periods. The 'ageing constant' calculated between years 8-17 was over 36000 years. Given this absurd figure, it should be clear that half-life models should not be used as a general means of design or specification for galvanic anodes and may be specific to a particular? anode type. Therefore, such models should not be used in the specification of anode systems beyond those of VCT. The model does not predict the current output of anodes manufactured by CPT, and care should be taken to apply such a model to any system distinct from VCT products. systems.

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