A Two-Stage Cathodic Protection System Combining ICCP Components with Long-Term Galvanic Anode Steel Reinforcement Protection

David Whitmore[#], David Simpson & George Sergi

[#]Vector Corrosion Technologies Ltd.
474 Dovercourt Drive
Winnipeg, MB, Canada R3Y 1G4
Tel: +1-204-489-6300

Abstract

Laboratory experiments established that corrosion of steel reinforcement can be arrested within relatively short periods if a sufficient cathodic current density higher than 20 mA/m^2 is applied. After corrosion is arrested, it is only necessary to maintain steel passivity longer-term by cathodic prevention, a process that requires a much-reduced current density. Once the two-stage principle was tested and established in the laboratory, self-contained anodes were developed, each product comprising a battery-operated Impressed Current Cathodic Protection element and a galvanic anode component. A high initial current output substantially above 20 mA/m^2 by area of steel is delivered over a period of weeks during which corrosion arrest is achieved. The galvanic anode components then deliver the lower cathodic prevention current long-term. This paper introduces the concept and principles of the technique, illustrates products developed and presents medium-term field studies to demonstrate the success of the Two-Stage CP technique.

Keywords
Galvanic anodes, Cathodic Protection, Corrosion control, Steel reinforcement

Background
There is no doubt that Impressed Current Cathodic Protection (ICCP) of steel reinforced concrete has, over the last decades, become a well-established technique for controlling reinforcement corrosion of structural elements. The expectation of long-life protection has, however, been somewhat reduced as some anode systems fail, monitoring equipment become antiquated, and lack of adequate maintenance makes the systems inoperable with the average service life of any ICCP system falling to 15-20 years.[1] Inevitable additional costs are involved in maintaining and prolonging correct operation of the system. It appears that there is a requirement by structure managers and owners for simpler cathodic protection (CP) systems which will involve less maintenance and monitoring requirements.

ISO EN 12696:2022[2] and NACE SP0290-2017[3] have clear performance criteria that need to be satisfied to ensure that a cathodic protection system is working. One popular criterion is a depolarization potential of 100 mV over a period of 24 hours. ISO EN 12696:2022[2] also defines in Figure A3 that a successful CP system either passivates the steel or reduces the corrosion rate of the steel reinforcement. The implication is that achieving 100 mV of polarization does not necessarily mean that corrosion has been arrested but that an acceptable reduction in corrosion can be achieved. Nonetheless, it has been shown that if a CP system had run for periods of around 5 years, and is then turned off, re-initiation of corrosion of the steel is avoided over a significant time period.[4] What appears to delay the onset of corrosion are some important secondary effects, primarily, the increase in alkalinity and reduction in chloride concentration at the

steel/concrete interface[5] which in effect reduces the [Cl⁻]/[OH⁻] ratio considerably below the critical ratio for initiation or maintenance of corrosion. Furthermore, re-alkalization of the acidified pits occurs which allows steel repassivation within them.[6] Once repassivation of the steel is achieved, it is reasonable to expect maintenance of the passive conditions long-term by the application of cathodic prevention.[7]

It is important, however, to identify the current density and overall charge delivery requirement for successful corrosion arrest of the steel reinforcement before reduction of the current density to the lower cathodic prevention levels (0.4-2 mA/m^2), which have been shown to be easily achieved by galvanic anodes.[4-6]

A series of laboratory experiments were conducted with the aim of developing a viable Stage-1 procedure in which corrosion arrest of corroding steel can be achieved. The results are published elsewhere.[8] Briefly, the tests showed that at two constant current levels, 30 mA/m^2 and 50 mA/m^2, the corrosion of pre-corroded steel plates in mortars was arrested after a length of time under polarization. The mortars contained increasing doses of chloride by weight of cement as NaCl. The required charge (current in amps multiplied by time in seconds) delivered to the steel until passivation of the steel increased with the level of chloride. Interestingly, the overall charge requirement was lower at the higher current density of 50 mA/m^2, as summarized in Table 1.

Table 1 *Cathodic Charge required to passivate steel at the chloride levels and current densities shown*

Current Density (mA/m^2)	30		50	
% Cl⁻ in Mortar (by cement wt.)	2	3	2	4
Cathodic Charge (kC/m^2)	120	190	74	108

Passivity of the steel was assumed when the 24-hour depolarized potential had reached -150mV vs Ag/AgCl, 0.5M KCl as indicated in EN 12696:2022[2].

Passivity of the steel can be maintained in a corrosive environment for considerable periods by Cathodic Prevention, (c.d. of 0.4-2 mA/m^2 of steel area) as Pedefferri[9] and Presuel-Monreno et al[10] had demonstrated. They more specifically showed that constant exposure to highly corrosive environments could not initiate corrosion at a cathodic prevention current density of 1 mA/m^2.[11] Once corrosion is arrested by a high initial current density, it would appear reasonable to suggest that Cathodic Prevention, as a second stage process, is likely to protect the steel from further corrosion in the long-term. A CP system based on a Two-Stage process, therefore, appears to be a viable corrosion mitigation method.

Understanding of this principle enabled the development of a simple to install and operate Two-Stage Corrosion Mitigation system[12,13,14] as illustrated in Figure 1.
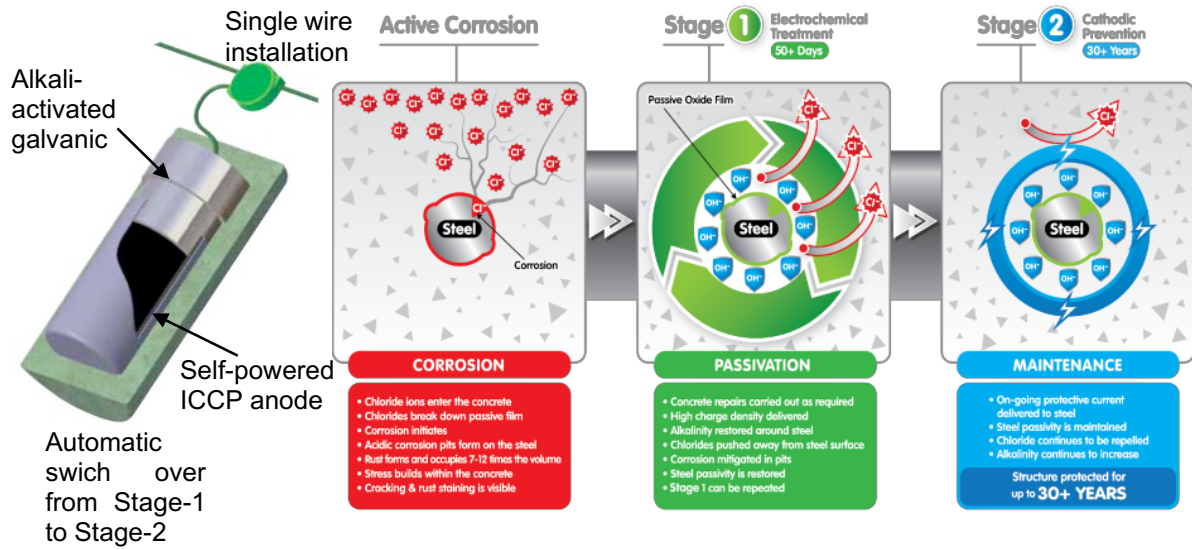
Figure 1 *Two-Stage anode system and schematic of its operation*

Some further laboratory tests involved monitoring of anodes in accelerated conditions in a chloride laden environment to ensure that current successfully switched from the ICCP element to the galvanic anode component smoothly (Fig. 2). It was also necessary to ensure that the stainless-steel current carrier in the ICCP component remained intact after delivery of the early high-level current. It is known that stainless steel can suffer from pitting corrosion in anodic conditions and to avoid this occurrence, the stainless steel was encased in a highly alkaline mortar saturated with lithium hydroxide which maintains a pH in excess of 14.5.
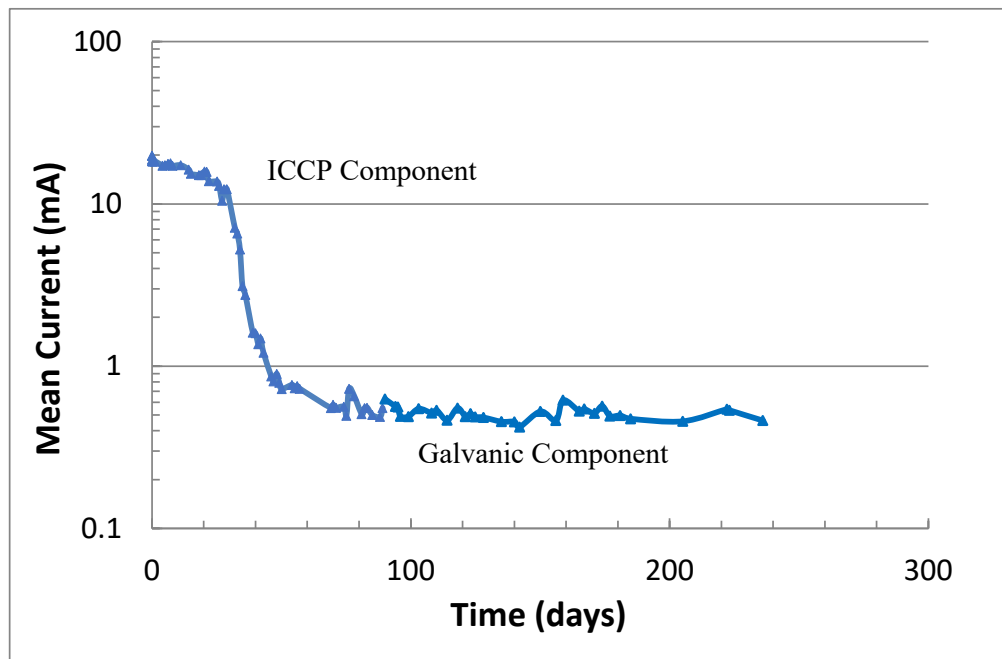

Figure 2 *Mean current delivery of 12 two-stage anodes in accelerated conditions showing smooth transition between the ICCP and galvanic components.*

Removal and study of the anodes after 240 days of testing, well beyond the Stage-1 process, revealed no signs of pitting of the stainless-steel current carriers (Fig. 3). Furthermore, the pH around the cans remained higher than 14.5 so protection against pitting was ensured. The pH was measured by neutralization of 2g samples of the mortar with 0.1 M nitric acid until a first inflection was observed, the plateau up to the inflection indicating the level of saturation of lithium hydroxide which has a pH of 14.6 at saturation.
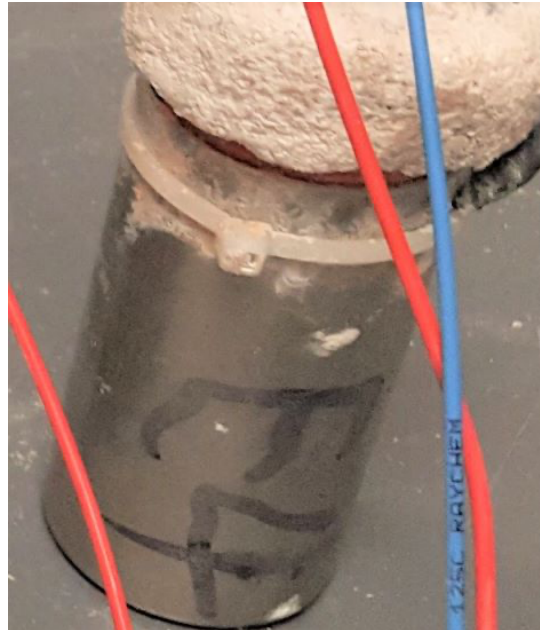

Figure 3 *An anode removed from the trial showing good condition of the stainless-steel ICCP anode component*

Field studies

After an initial trial on a single column of a bridge in the UK where a total of 18 of these Two-Stage anodes were successfully tested over a period of nearly three years,[13] a project was carried out on a structure in South Wales, UK. Two piers of the Bridge had suffered from typical steel reinforcement corrosion with cracking and spalling of the concrete in places. Corrosion was caused by chlorides leaking from a joint above the crossbeams and it affected the abutments, the top of the piers and parts of the columns (Fig. 4). Following a detailed survey, a Two-Stage CP system was designed. The design considerations are detailed in an earlier publication which also shows the early results.[14] Calculations determined that an anode spacing of 500 mm on center was expected to exceed considerably the minimum charge requirement of around 300 kC/m^2 and was chosen as the standard spacing for both piers. The level of charge was chosen to be at least twice the minimum required for 2% chloride contamination around the steel reinforcement (Table 1) to ensure that at least the minimum charge is delivered to areas of the steel in-between the anodes. The spacing also ensured sufficient current density for the Stage-2 cathodic prevention period of 30 years.

In this paper, the results up to nearly 2 years since installation and commissioning are detailed and conclusions as of the success of the system are drawn out.

Figure 4 Part of Pier-2 in the bridge in South Wales showing the Abutment in the background (left) and typical damage of the structure from chloride-induced corrosion of the steel reinforcement (right)

Results and Discussion

Monitoring of the system was performed using an in-situ data logger system with data collection able to be transmitted via the internet. The system allowed disconnection of the anodes, instant-off potential measurements and 24-hour depolarization measurements as required.

The current delivery of each chain of anodes of up to 25 to the steel reinforcement in two separate zones, converted to current density by area of steel (all the steel in the zone plus 10%), is shown in Figure 5. Data over a period between 350 days and 600 days were not available, but the switch over from Stage-1 to Stage-2, which occurred over a period of around 200 days, is clearly demonstrated. An early current density of the order of 30-80 mA/m^2 was recorded but a subsequent constant cathodic prevention level of a mean of 1-2 mA/m^2 was delivered during the subsequent Stage-2 period. This second level of current is expected to be delivered over subsequent years by the galvanic anodes.
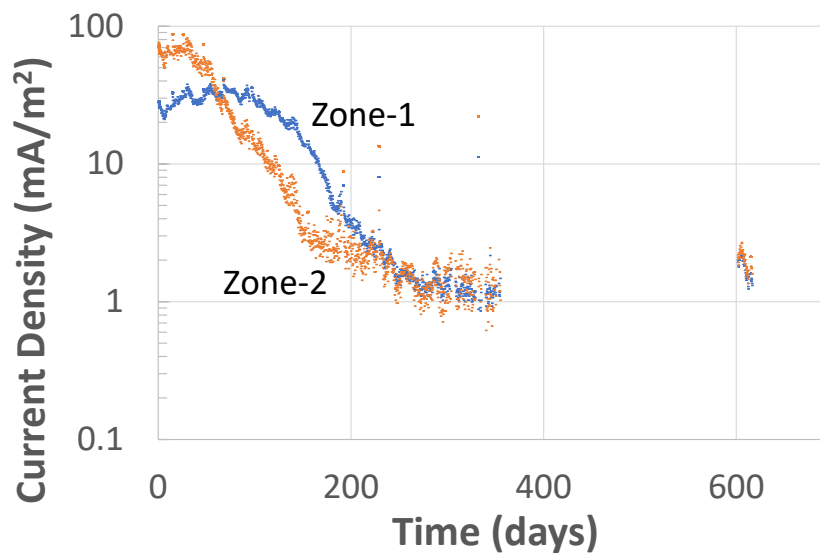

Figure 5 Current density delivered to the steel within two monitored zones of the structure.

The equivalent cumulative charge exceeded the minimum design requirement for Stage-1 of 300 kC/m^2 well within 200 days, as seen in Figure 6.
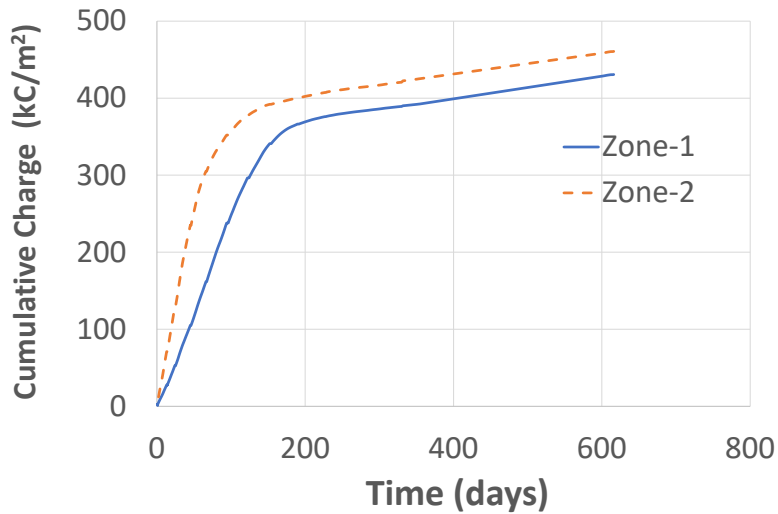

Figure 6 *Cumulative charge delivered to the steel indicating a sharp delivery of well over 300 kC/m^2 over a period of less than 200 days.*

A total of nine depolarizations were performed over the period. The 24-hour depolarized potentials experienced a constant shift in the positive direction, reaching or exceeding a level considered as passive (-150 mV vs. Silver/silver chloride, 0.5 M KCl reference electrode) within 100-120 days, i.e. within Stage-1 (Fig. 7).
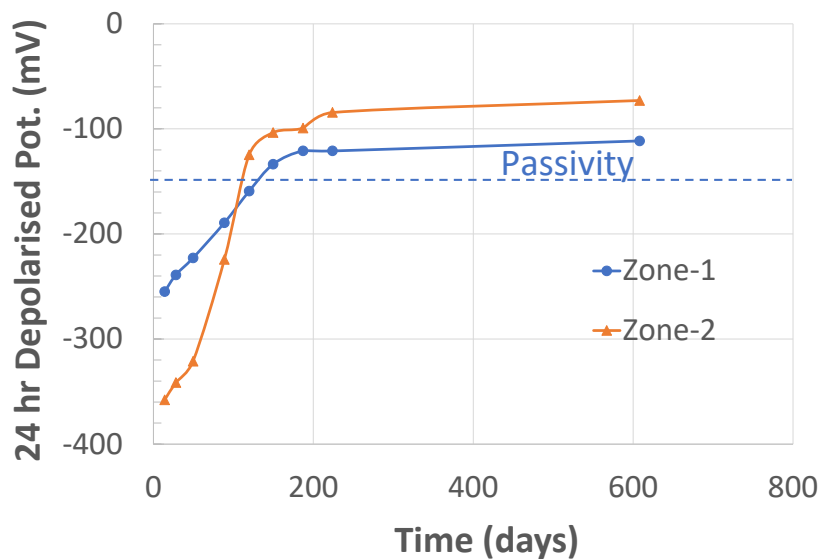

Figure 7 *Change in the mean depolarized potential of the steel in Zones-1 & 2, as recorded 24 hours after disconnection of the anodes.*

The level of depolarization over 24 hours (the difference between the instant-off and depolarized potentials) was very high during Stage-1, as might have been expected by the very high current densities

and reached a maximum of 180-230 mV. Subsequently it fell to around 50 mV owing to the lower cathodic prevention current densities (Fig. 8). Early instant off potentials ranged between -350 mV and -600 mV.
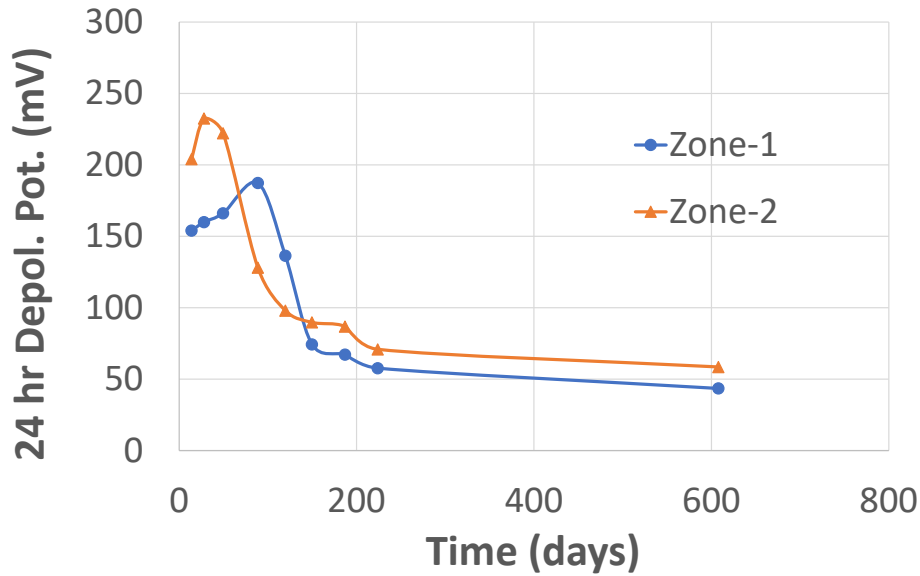

Figure 8 *Change of 24-hour depolarization potentials with time.*

Earlier experimental and site work[8] suggested that an apparent corrosion current density ($i_{corr(app)}$) could be estimated using the Butler Volmer equation (eq. 1).

$$i_{corr(app)} = \frac{i_{appl}}{exp\left(\frac{2.3\eta}{\beta a}\right) - exp\left(\frac{-2.3\eta}{\beta c}\right)} \qquad (1)$$

Where,

$i_{corr(app)}$ = apparent corrosion current density,
i_{appl} = applied current, i.e. current density,
η = potential shift, i.e. depolarization potential,
βa = Anodic Tafel Constant,
βc = Cathodic Tafel Constant.

The Tafel constants above are assumed to be 120 mV but it is known that the cathodic Tafel constant can vary and can have a major influence on the calculated corrosion rate.[15] Furthermore, owing to factors such as the uncertainty of the steel area to which the current is delivered, variations in current throw with changing concrete resistance, uncertainty of the level of polarization and unreliability of potential measurements, such calculations can only offer a rough estimation of corrosion current density. As the parameters are measured in a reproducible way, the trend of the measurements can offer confirmation of a reducing corrosion rate which, in combination with the depolarized potential (Fig. 7) can offer confidence in the success of this type of CP technique. The mean apparent corrosion current densities of the two zones are depicted in Figures 9. Both show an overall decreasing trend in the corrosion activity of the steel reinforcement.
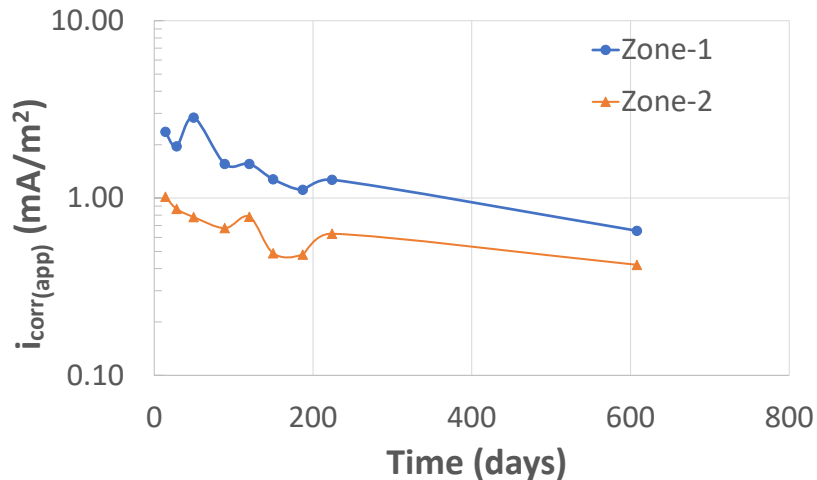
Figure 9 *Reduction of apparent corrosion current density with time of polarization.*

Conclusions

A Two-Stage anode (ICCP/galvanic anode) was designed based on earlier laboratory research. It was shown to arrest corrosion and maintain a current output consistent with cathodic prevention both in the laboratory tests and on real structures.

The charge required to establish steel passivity was shown in laboratory tests to be related to the level of chloride in the concrete around the reinforcement. A pre-determined level for the structure in Wales of 300 kC/m^2 by steel area, was found to be adequate to arrest corrosion. Nonetheless, design should be based on sound engineering judgement and not only on chloride level.

A potential more noble than -150 mV vs a standard silver/silver chloride electrode is suggested as a level indicating passivity and was shown to have been established around the time Stage-1 of the process was completed.

Use of the Butler Volmer equation to estimate an apparent corrosion current density using determined parameters of current density and depolarization was shown to be useful in demonstrating a reduction in corrosion level.

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