ARTICLE

Electromagnetic induction corrosion control technology (EICCT)

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Over the past several years, a new corrosion control technology has been developed for protecting damaged, painted galvanized, and galvannealed surfaces in contact with ambient aqueous environments. This technology, which we call electromagnetically induced corrosion control technology (EICCT), is an electronic technology that is based upon coupling surface currents into the metal structure to be protected. Electromagnetic induction experiments have demonstrated that the induced current is spread across the surfaces of complex shapes, such as an automobile body, as required by Maxwell's equations, so that induction at a single point is effective in protecting a whole, complex-shaped surface, that the power consumption is very low, and possibly that the induced signal may be tailored to optimize the efficacy. The observed efficacy is attributed to inhibition of zinc passivation as directly indicated by the coupling current. Efficacy is also indicated by inhibition of rusting at scribes in painted panels. It is important to emphasize that the technique is not a classical, impressed current cathodic protection (ICCP) system.

KEYWORDS
automobile corrosion, electromagnetic induction corrosion control technology, galvanized steel, galvannealed steel, surface currents

1 | INTRODUCTION

This paper describes the evaluation of a new corrosion control technology, electromagnetic induction corrosion control technology (EICCT), which has been found to protect painted galvanized steel panels at damage sites where bare steel is exposed. To our knowledge, this technology has only once been previously described in the open, scientific literature, and that was by the present authors,[1] but its efficacy is such

that it might find widespread use in protecting painted, galvanized steel structures (e.g., automobile bodies, roofing, guard rails, and light standards). The surface currents that are postulated to be responsible for protection are induced into the metal structure by a pulse generator, hereafter termed the Module. Some technical details of the Module are given below.

Prior to initiating the present work, early versions of the Module had been evaluated in subjective experiments by

Underwriters Laboratories of Canada (ULC)[2] and by Smithers Scientific Services (SSS)[3]; these Modules were known as Final Coat and Body Guard, respectively. The ULC and SSS evaluations were subjective in that the differences between the protected (with a Module) and unprotected (without a Module) as assessed visually after exposure in a salt-spray cabinet under well-controlled conditions. The tests were carried out in accordance with ASTM standards (D 1654, Test Methods for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments), with each test panel being scribed through the coating into the underlying steel. In both studies, the panels that were connected to the Module displayed significantly less corrosion than did the control panels, which were identical in all other respects. The experiments described below were performed to quantitatively examine the efficacy of EICCT over a surface in the absence of an electrolyte film between the point of application of the electrical signal from the Module and the area being protected and to indicate, to the greatest extent possible, the mechanism by which the Module provides protection against corrosion. One of the principal problems in assessing the effectiveness of the Module lies in ascertaining exactly how the device achieves corrosion control, since it is not a classical impressed current cathodic protection (ICCP) system, in which current is projected through an ionically conducting (aqueous) phase from an anode to the point on a component that needs to be protected, such that the potential of the component is displaced in the negative direction. The ICCP approach has been demonstrated by Baboian[4] to be impractical on a vehicle, because of the excessively high resistance through the surface electrolyte film between the damage (the cathode) and the anode in any practical configuration. The experiments described below measures the Module's effect on the potential of a scribed region (exposed steel) on a test panel in the absence of a continuous electrolyte film (aqueous phase) between the point of application of the electrical signal from the Module and the area being protected. Under these circumstances, classical ICCP is impossible, because a return path for the current from the scribe to the anode through an electrolyte film does not exist and because no anode exists on the surface. Accordingly, a positive result from these experiments will demonstrate that the Module is effective in protecting painted, galvanized or galvannealed steel panels, as evidenced by a shift in the potential of the exposed steel at the scribe in the negative direction. As noted above, the mechanism of protection provided by the Module is not that of classical ICCP and the reader needs to carefully distinguish between the two. Additionally, as indicated below, the current or voltage applied to a panel by the Module is in the form of a repetitive pulse and not as a direct current that is employed in ICCP systems, again demonstrating a vital difference between the latter and the Module. Work is currently underway to enhance the efficacy of EICCT by tailoring the form of the induced current delivered by the module.

2 | EXPERIMENTAL

The current paper describes three sets of experiments that were carried out to evaluate the efficacy of EICCT: spray experiments, laminated (galvanic coupling) experiments, and salt fog experiments.

2.1 | Spray experiments

In this first set of experiments, three of the five experiments used two automobile stock galvannealed steel panels per experiment, each measuring 1.22 m by 0.914 m, which were coated on both sides with DUPONT 72400 by Northwest Campus Auto Body located in Columbus, OH. (These first three experiments were performed at CC Technologies, now DNV Columbus, Columbus, OH, under contract to Canadian Auto Preservation and under the direction of Dr. Digby D. Macdonald.) This is a standard coating system for exterior automobile bodies and the test efficacy was indicated by the ability of the Module to displace the corrosion potential at the scribe. The other two of the five experiments in the first set used galvannealed steel (Sparta Steel), painted and clear-coated with a standard automotive coating system. The panels in each experiment were identical in all material respects. The panels were scribed to cut through the clear coat, paint, and galvannealed layer, thereby exposing the bare steel. A reference electrode was placed at the location of the scribe on each panel to monitor the corrosion potential of each panel. The reference electrode comprised a Ag/AgCl + KCl (sat) active element and employed a Luggin capillary connected to the panel from the back side. Electrolytic communication between the scribe and the liquid junction of the Luggin capillary was effected by a small diameter (3.5 mm) hole drilled through the panel within the scribe. The potential of the exposed steel at the scribe, as measured against the reference electrode, was recorded using a high impedance voltmeter/data logger.

One of the panels (the test panel) was connected to the Module, with the Module and the lead wire being attached on the back side of the test panel. Even though a small bolt was used to fix the wire, the point of connection was well above the spray zone. In this way, any possibility of the inadvertent development of an electrolyte path between the Module connection to the panel and the scribe was eliminated; in any event the Module connection is in ohmic contact with the panel and cannot act as the anode in a classical ICCP system. The connection of the Module to the backside of the panel and the entire electrical circuitry is shown in Figure 1. The other panel (the control panel) was not connected to a Module. Both
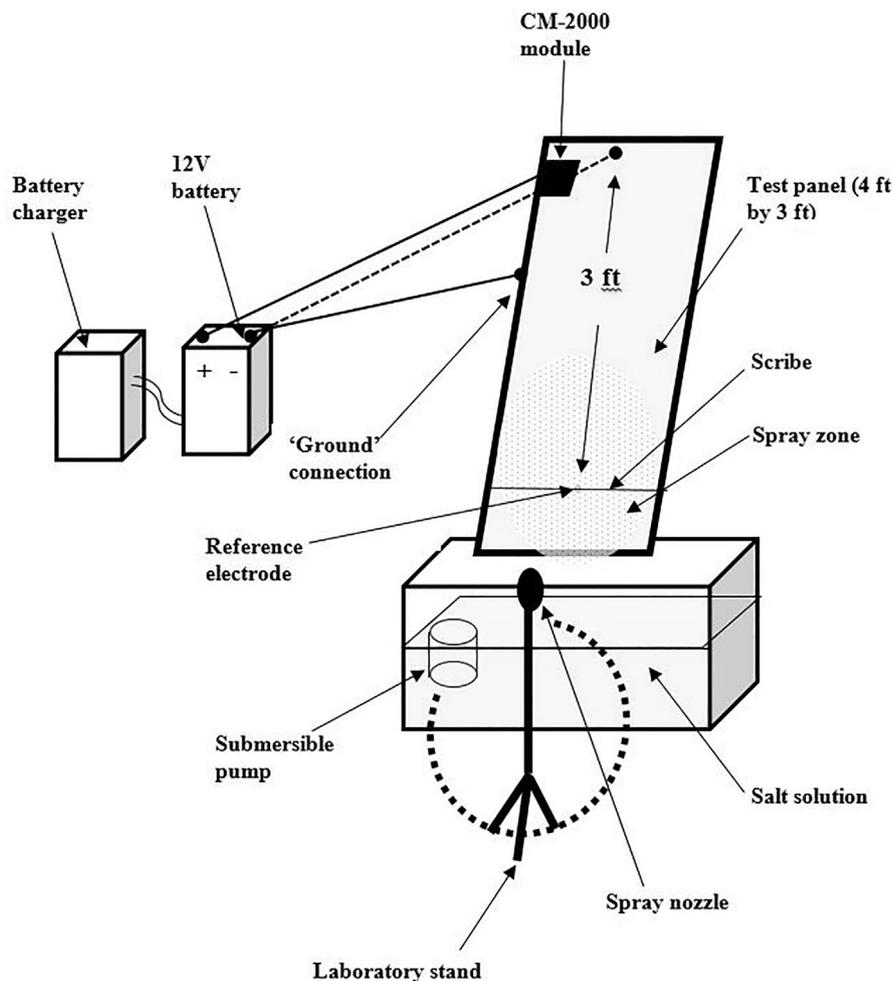
FIGURE 1 Configuration of the test panel showing the location of the module at the back to avoid any contact with the testing solution, the scribe, the spray zone, and spray nozzle (continuously sprayed with a 3.6 wt% NaCl). The control panel was identical in all material respects

panels were inclined at 25° to the vertical with the scribed surface facing outward and with the scribe being located approximately 3 feet down from the top edge. The scribed surfaces of the panels were continuously sprayed with a 3.6 wt% NaCl (salt) solution to simulate road salt exposure. Only the surface of the panel in the vicinity of the scribe, and the surface below, was inundated with the electrolyte (see Figure 1); the remainder of the panel surface remained dry. In fact, the distance between the top of the spray zone and the location where the Module was connected to the test panel was approximately 2 feet showing that any possibility of a return electrolyte path can be discounted. In addition, as noted above, the lead wire for the Module was connected to the back of the test panel, which was not in contact with the electrolyte plume.

With the exception of the presence of the Module on the test panel, we emphasize again that the configurations of the test and control panels were identical in all material respects. The progression of corrosion was quantified by measuring the corrosion potentials and was also characterized visually by examining the rust stains emanating from the scribes.

2.2 | Laminate experiments

This second set of experiments comprised laminated steel, epoxy, zinc, epoxy structures formed with $1.27 \, cm \times 10.2 \, cm$ zinc foil (0.0254 mm thick) glued to coated $0.6096 \, m \times 0.9144 \, m$ steel panels, with the zinc then being covered by a layer of two-part epoxy (Devcon or generic long-curing epoxy), as shown schematically in Figure 2. The steel panel was connected to ground, while the zinc foil was connected to ground using an insulated wire and a zero resistance ammeter (ZRA), also shown in Figure 2. In this configuration with negative feedback, the amplifier (ZRA) provides an output that drives the potential of the zinc foil to virtual ground (within a microvolt), a condition that would exist if the zinc and the steel were in ohmic contact. The current that is required to maintain this condition is termed the coupling current and is a measure of
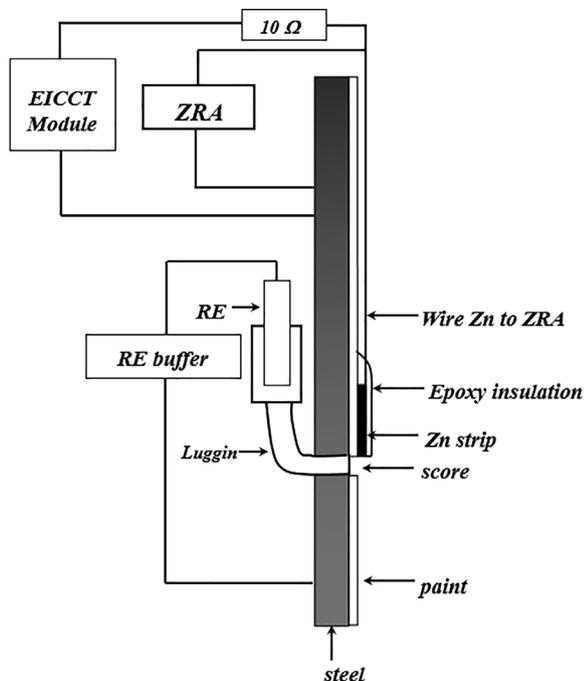
FIGURE 2 Laminate experiments schematics of zero resistance ammeter (ZRA) used for measuring the coupling current between the zinc strip and the steel phases

the current that flows between the steel and zinc members of a galvanic couple.

These specimens were also equipped with Ag/AgCl + KCl (sat) reference electrodes/Luggin probes that protruded through the specimen from the back side into a scribe on the front of the specimen that penetrated through the paint and zinc layers to the underlying steel, as indicated in Figure 2. The spray setup used in these experiments was similar to that used in the spray experiments.

2.3 | Salt-fog experiments

The third set of experiments that are reported upon in this paper involved exposure of scribed panels to a salt fog within an environmentally-controlled chamber. The continuous salt fog experiments were conducted in Q-LAB's Model CCT-1100 cyclic corrosion chambers, with one chamber containing unprotected panels (control panels) while the other contained protected panels (test panels). This arrangement is unusual, but was necessary due to the nature of the corrosion reduction phenomenon. As discussed above, the Module operates by exciting transient surface currents by the application of a capacitively-couple voltage source. Being a time varying electromagnetic signal, it is possible for excited panels to induce surface currents into nearby panels that are not directly connected to a Module. To ensure that this does not happen it is necessary to employ two corrosion chambers

separated by a sufficient distance, while maintaining identical environments in both.

The temperature was 35 °C, the corrosion cycle was a continuous fog with a fallout rate of 1–2 mL/h (per 80 cm^2 area), and the electrolyte was 0.01 M Na$_2$CO$_3$ to achieve the zinc passive state.[5] Since two different chambers are employed, it is vital that the temperature and fallout rate are kept the same. To this end, the fallout rate was monitored and recorded every day. During each recording the fallout rate at six locations within each chamber was recorded to ensure that the fallout is uniform within the chamber. It was also verified that the total fallout rate in each chamber is within 10% of each other.

During the first two experiments, four control and four test panels were employed. In all subsequent experiments, eight panels were used. This was done to achieve a more accurate statistical measure of corrosion damage as reflected by the area of the scribe that was protected. Fallout of the fog onto the panels is a random process with some panels wetted more than others resulting in different amounts of corrosion on the panels within the same chamber. In order to account for this phenomenon, it is necessary to employ a sufficiently large number of panels to obtain an average wetting and hence the average corrosion damage. The electro-galvanized panels measured 15.24 cm × 20.32 cm and were obtained from ACT. Each panel was painted according to automotive standards and included a clear-coat top layer. The attachment of the module to the test (protected) panels was made at four points (connections protected by epoxy putty) along the top and bottom 15.24 cm edge. This multiple point connection was made to more uniformly launch the currents across the panels. The scratches were made with a ceramic cutoff wheel inserted in a standard Dremel tool. The scratches are approximately 0.812 mm wide and 10.15 cm in length and penetrate down to the steel. All test (protected) panels were protected with production versions of the CM3000 module. As evidenced by the experiments described herein, the Module does not require a continuous aqueous phase to exist between the corrosion site and the point of application of the electrical signal, as is the case for an impressed current cathodic protection (ICCP) system. This is a consequence of the surface currents that are generated by the Module; surface currents that are essentially present over the entire metal surface (see section 2.4).

2.4 | The Module output

The Module consists of a pulsed voltage source capacitively coupled to the metallic object to be protected. The Module is powered by a suitable DC power source. A simplified schematic is shown in Figure 3.
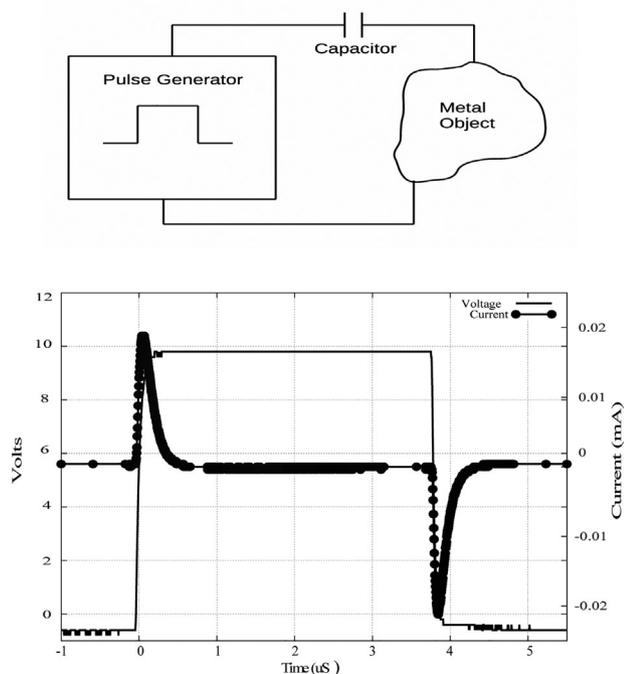
FIGURE 3 The Module output. Pulse voltage generator and capacitor coupled to the metal (top) and the applied voltage and current generated profile for the CM-3000 Module (bottom)

The pulsed voltage source generates a voltage pulse with an amplitude of 10 V, pulse width of 3 µs, repetition period of 100 µs, and rise and fall times of 100 ns (nominal values).

The pulsed voltage source is coupled to the body to be protected through a capacitor as shown in Figure 3. From basic electronics we know that the capacitor essentially differentiates the voltage pulse and a pulsed current flows through the circuit, which includes the body to be protected. The relevant equation is

$$i = C\frac{dV}{dt},\qquad(1)$$

where i is the current, V is the applied voltage, and t is time. The voltage pulse and the current pulses it generates are shown in Figure 3.

This current pulse is very fast and flows primarily in the surface of the metal. The current is constrained to the surface of the metal as a consequence of the skin effect, a phenomenon described by Maxwell's equations when high-frequency signals are present within a conductor. One who is familiar with Fourier transforms will recognize that such a signal is rich in high frequency components. In this case, these range from approximately 10 kHz to 3.5 MHz At these frequencies the skin effect is pronounced.

Calculations using standard electromagnetic theory indicates that at a frequency of 1.5 MHz, the skin depth in zinc is 100 µm and within steel it is 16 µm. Clearly, then most of the current flows in the surface. Corrosion being a surface phenomenon, these currents are present at the right place to interfere with the corrosion process.

Unlike impressed current cathodic protection systems, the Module's effect is not limited to the region where a continuous electrolyte film exists between the point of application of the electrical signal (the anode) and the area being protected. The surface current generated by the Module propagates over the entire surface. Thus, by virtue of the generated surface currents, the Module is able to depassivate the zinc, thereby, reducing the corrosion of steel compared to the condition where zinc is passivated and unable to perform its desired function.

That the surface currents are well distributed over the surface was shown by testing at the Ohio State Electroscience Laboratory. In this test, an automobile (Buick Century) was used as the test specimen.[6] The induced current was detected at fifty-eight locations across the body of the automobile. It was found that the induced surface current was well distributed across the entire surface in spite of the complex shape of the vehicle. As noted above, this result is fully consistent with the predictions of modern electrodynamics (i.e., via Maxwell's equations).

3 | RESULTS AND DISCUSSION

3.1 | Spray experiments

As outlined in greater detail below, the test panel (which was connected to the Module) showed marked differences in corrosion potentials when compared with the control panel. Five such experiments are described here. Each of the five experiments yielded broadly consistent results. Specifically, the potential for the test panel eventually became more negative than that for the control panel by approximately 150 mV. In addition, the difference in corrosion potential is also supported by the difference in the rust staining
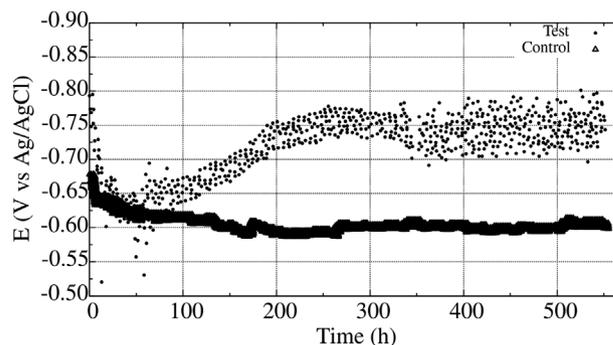

FIGURE 4 Corrosion potential versus time for the test and control panels (galvannealed steel) sprayed with a 3.6 wt% NaCl solution over 550 h

characteristics of the test panel, when compared with the control panel, and are supported by the coupling current and salt fog experimental results that will be discussed later in the paper.

During the first experiment of the salt spray, the corrosion potentials measured at the scribes on both panels were approximately the same until the experiment had been conducted for approximately 50 h. The potentials then diverged, with that for the test panel eventually becoming more negative than that for the control panel. This significant difference in corrosion potential continued until the experiment was terminated following 550 h of exposure. A plot showing the corrosion potential versus time over the duration of the entire experiment for the test and control panels is given in Figure 4. It is also noted that the noise in the test panel potential is significantly greater than that for the control panel. The fluctuations in the test panel potential are to be expected, because the panel is under active electrochemical control from the Module, in which the efficacy of the Module may vary from time-to-time as the local conditions change (the growth and detachment of gas bubbles, release of dissolved air in the electrolyte, etc). In any event, the role of the Module in displacing the potential of the scribed area in the negative direction is clear.

Photographs of the two sets of panels at the termination of the experiment are shown in Figure 5. These tests showed
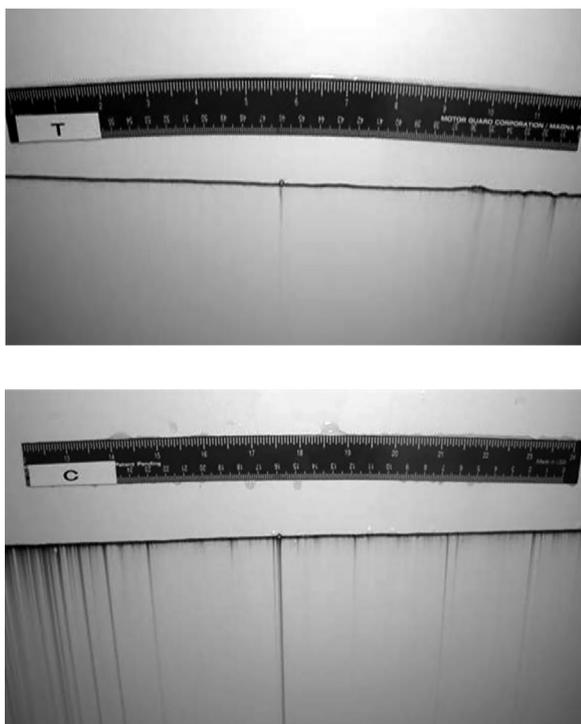
marked differences in the extent of rust staining from the scribes on the test panel and the control panel from very short times. The fact that any staining is observed on the test panel can be attributed to corrosion during an induction period that exists for the efficacy of the Module to develop. Thus, with reference to Figure 4, the impact of the Module on the corrosion potential of the scribe is evident only after about 50 h of exposure, during which time rust would have accumulated on the test panel to the same extent that it accumulated on the control panel. In other words, we postulate that the rust that accumulates on the test panel did so during the induction period. After that time, very little corrosion, if any, occurs on the test panel as the Module takes effect. Because, in automobile protection, we are concerned with long term effects ($\gg$100 h), we conclude that the Module is effective to the extent that little or no additional rust staining would have been observed after the initial 50-h exposure period, in this case. Clearly, any staining that would have occurred during the induction period might reasonably be expected to be cleaned from the automobile body early in the life of the vehicle. The present data suggest that, thereafter, the accumulation of rust staining on a vehicle protected by the Module should be minimal, if not non-existent. The first five experiments were not temperature controlled, so the experiments were conducted at prevailing ambient temperature. Later experiments were conducted in the fall where the average ambient temperature was lower, which was correlated with the longer induction times.

In the other four experiments, the time required to establish a significant difference in corrosion potential and the amount of rust staining was different than in the first experiment. This is consistent with the existence of an induction time for the Module to begin to exert control over the corrosion process, as noted above, and it is the goal of future work to understand the processes that control the length of the induction period. Some results of the second, third, fourth, and fifth experiments are shown in Figures 6–8. It is important to note that this series of experiments were carried out at ambient temperature in a room that was not temperature
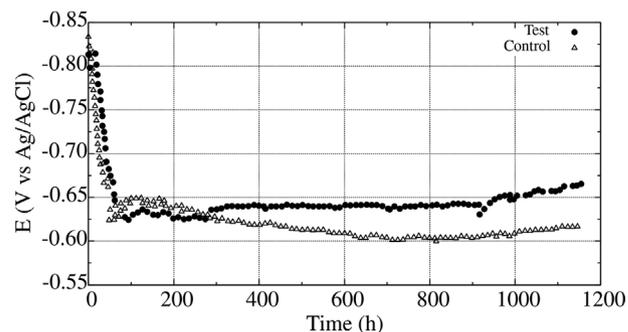

FIGURE 5 Visual inspection of the galvannealed steel test panel (top) and control panel (bottom) sprayed with a 3.6 wt% NaCl solution over 550 h

FIGURE 6 Corrosion potential versus time for the test and control panels (galvannealed steel) sprayed with a 3.6 wt% NaCl solution over 1150 h
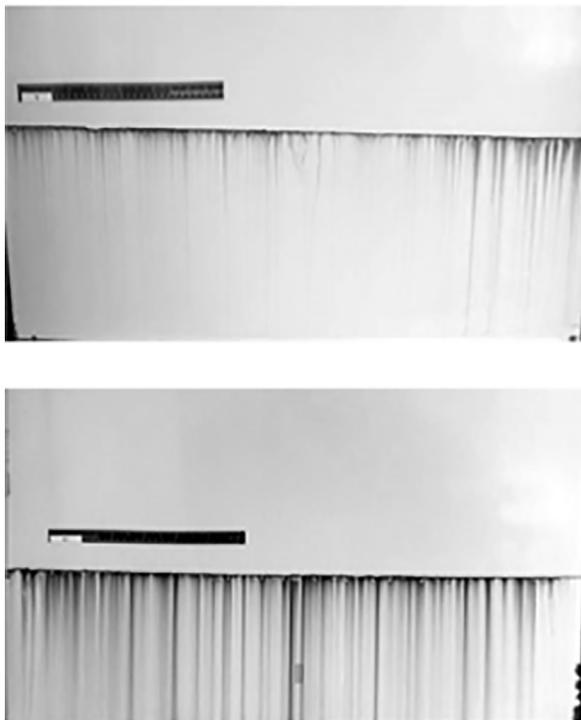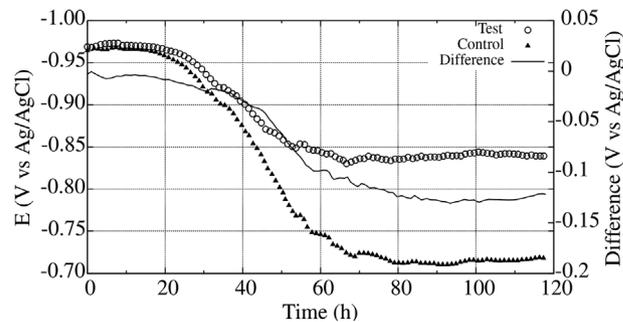
FIGURE 8 Corrosion potential versus time for the test and control panels (galvannealed steel) sprayed with a 3.6 wt% NaCl solution over 120 h and potential difference versus time (bottom)

$CR_{test}/CR_{control} = 0.00291$. That is, the corrosion rate is reduced by 99.7% by the Module on the test panel compared with the control panel. Even if the difference in the corrosion potential is reduced to 0.100 V, the ratio $CR_{test}/CR_{control} = 0.0204$ and hence the corrosion rate is reduced by 98%. To put these numbers in perspective, imagine that a system (e.g., an automobile panel) fails by corrosion without the Module in a time of one year. If the Module were attached, the failure time would be 343 years, if the potential is displaced by 150 mV in the negative direction and would be 49 years if the potential was displaced by only 100 mV. Such results are particularly significant, when one considers that the average life of a vehicle is of the order of 10 years and that the consequences of rusting are mostly cosmetic in nature. Accordingly, these calculations demonstrate that the reduction in corrosion rate is substantial and that the Module appears to be an effective corrosion control device.

It is evident from the potential versus time data plotted in Figures, 4, 6 and 8 that a considerable induction time may exist before the Module causes reactivation of the galvanizing. For the five experiments, the induction times were 50, 250, 450, 384, and 72 h, respectively. Indeed, two experiments were conducted in which the systems remained within the induction period for approximately 1000 h, over which no

FIGURE 7 Visual inspection of the galvannealed steel test panel (top) and control panel (bottom) sprayed with a 3.6 wt% NaCl solution over 1150 h

controlled. Since the experiments were carried out over a 6-month period, some of the run-to-run variability might be attributed to variation in the temperature. All subsequent experiments were controlled at the indicated temperatures.

The effect of a 150 mV difference in the corrosion potential on the rate of corrosion of an automobile body panel is significant and may be determined by applying the following formula, which is derived from electrochemical kinetic (Tafel) theory:

$$CR = CR^0 \exp[\alpha F(E_{corr} - E_{corr}^0)/RT], \qquad (2)$$

where CR is the corrosion rate, CR^0 is the corrosion rate under reference conditions, α is the transfer coefficient, F is Faraday's constant (96.487 C mol^{-1}), R is the universal gas constant (8.314 J K^{-1} mol^{-1}), T is the Kelvin temperature (298.15 K), E_{corr} is the corrosion potential, and E_{corr}^0 is the corrosion potential under the reference conditions. This equation holds for all values of the corrosion potential within the active dissolution region for iron and hence by selecting the control panel as the reference system, we may write:

$$\frac{CR_{test}}{CR_{control}} = \exp[\alpha F(E_{corr} - E_{corr}^0)/RT], \qquad (3)$$

where $E_{corr} - E_{corr}^0 = -0.150$ V and $\alpha = 1.0$.[7] Substitution of the values for the various parameters yields
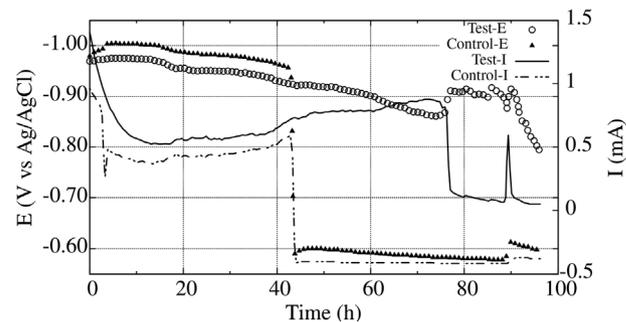

FIGURE 9 Corrosion potential and galvanic current versus time for the test and control panels (zinc/carbon steel laminate) sprayed with a 3.6 wt% NaCl solution over 90 h

difference was evident in the corrosion characteristics of the test and control panels, at least as indicated by the corrosion potential. While induction times of these magnitudes are not particularly important in the protection of automobiles, because of the long service times, a complete account of the mechanism of protection will require an unraveling of the factors that determine the induction time.

3.2 | Laminate experiments

Results from a typical coupling current experiment are shown in Figure 9. The coupling current data plotted shows that, initially, the coupling currents are both positive corresponding to the flow of electron current from the zinc to the steel. This is the expected flow, indicating that the zinc is acting as a sacrificial anode in protecting the steel. However, after 44 h, the coupling current of the control specimen that was not equipped with a CM3000 Module suddenly became negative, with the electron current flowing from the steel to the zinc. Thus, this "polarity reversal" indicates that the zinc was now acting as a cathode and hence was no longer acting as a sacrificial anode. On the other hand, the coupling current of the test specimen that was equipped with a CM3000 Module remained positive until the experiment was terminated. Simultaneously with the change in the sign of the coupling current, the measured corrosion potential at the scribe on the control specimen is observed to suddenly shift in the positive direction, as indicated in Figure 9, marking the end of the induction period. In the case of the test specimen, which was equipped with a CM3000 Module, the corrosion potential remains highly negative for the duration of the experiment. It is evident from these findings that the induction time corresponds to that time that the system (control panel) takes to achieve polarity reversal, and hence is a function of the properties of the environment, rather than of the performance of the Module.

The laminate experiments were repeated many times and significant variability was observed in the results. Some of this variability was in the form of not observing polarity reversal at all, in which case the zinc in both the test and control panels corrode in the active state. In other cases, it appeared that the zinc in both panels was in the passivated state to begin with. Clearly, understanding of the induction time is key to optimizing EICCT and our current research is directed to that end. That polarity reversal is a very complicated and poorly reproducible phenomenon, is amply clear from the many previous studies.[8–14]

The data presented in Figure 9 provide direct evidence that the CM3000 Module causes the zinc to remain anodic to steel by preventing the passivation of the zinc. This allows the galvanized coating to serve as a sacrificial anode, in contrast to the control specimen which suffered a polarity reversal due to the zinc becoming cathodic to steel. We also observed in a number of laminate experiments (not shown here), that

operation of the Module leads to an accelerated dissolution of the zinc and a greater galvanic current. Numerical integration of the galvanic current yielded a net charge of 206 C for the test panel and 3.8 C for the control panel. This is consistent with zinc activation (on the test panel) for much greater time, while the control panel suffered polarity reversal, but is inconsistent with the idea of cathodic inhibition of the oxygen reduction reaction on the iron. We observed a sharp current decrease on the test panel at 76 h. This sharp decrease reflects an abrupt increase in the impedance between the zinc and steel, possibly due to a partial zinc passivation. We note that during review, a referee suggested that this decrease in the coupling current could be alternatively explained by inhibition of the cathodic reduction of oxygen on the steel electrode. The evidence they pointed out for this was that the coupled potential remained relatively active despite the sharp decrease in the galvanic current. While we feel that the observations are better accounted for by the state of the zinc electrode (particularly, the large charge passed during coupling, as well as the polarity reversal observed on the control specimen), we are planning experiments in our laboratory to test this alternative explanation.

The passivation of zinc and polarity reversal, as observed in this work, is a well-established phenomenon in galvanized steel science,[8–15] being first reported in 1939 by Schikorr.[8] Szabo and Bakos,[14] for example, note that polarity reversal occurs under atmospheric conditions, resulting from the passivation of the zinc by zinc corrosion products. The zinc then acts as a cathode for the reduction of oxygen, resulting in a reversal of current flow, and no longer acts as a sacrificial anode. This same phenomenon occurs in oxygenated solutions of the type employed in the present study. Other workers have drawn attention to the apparent tendency of galvanized steel to polarity reversal as a function of temperature and water chemistry. Thus, the presence of bicarbonate ion is noted[10,13,16] as being the most important species favoring polarity reversal, while others include carbonate, nitrate and phosphate.[16] Ions that inhibit polarity reversal by maintaining the zinc in the active state are reported to be sulfate and chloride, in keeping with the observation that galvanizing is most effective in protecting iron in salt- or brackish-water.[12] However, polarity reversal has been reported in seawater when both the hydrostatic pressure and iron content of the alloy are high.[11,12] Other studies report that polarity reversal is thermally activated and, hence, that temperature is the most important factor in its induction,[15] with a temperature between 25 and 80 °C being necessary. However, others (including the authors in this work) have observed polarity reversal at ambient temperature, so that elevated temperature does not appear to be a necessary condition. According to Glass and Ashworth,[13] passivation of the zinc is caused by the precipitation of insulating zinc carbonates, a conclusion that was drawn from
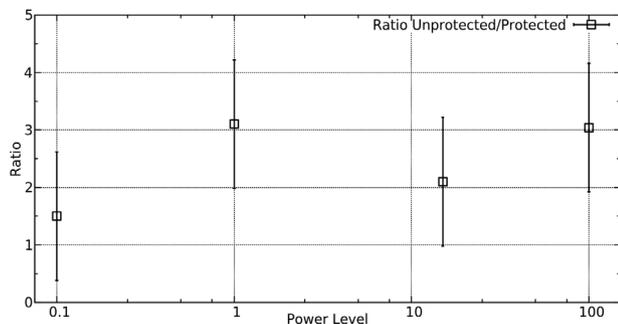
FIGURE 10 Salt fog experiments evaluation. Ratio of control corroded length to test corroded length at a scribe as a function of the power level of the Module. Uncertainties are ±1 standard deviation at 100% power

TABLE 1 Ratio of control corroded length to test corroded length for the five 100% power experiments and one experiment of 85% lower power

Experiment	Ratio	Notes
1	3.85	4 panels
2	0.95	4 panels[a]
3	1.31	8 panels
4	1.61	8 panels
5	7.65	8 panels
6	2.36	8 panels[b]

[a]Panels wiped down with denatured alcohol.
[b]Surface currents were 15% of those in Experiments 1–5.

a thermodynamic analysis and not from positive identification via surface analysis. It is evident from this brief review that the conditions leading to polarity reversal are not well defined, most probably due to inconsistent experimental findings between the various groups involved in this type of work.

3.3 | Salt-fog experiments

To evaluate the salt fog experiments the following method was employed: For each test (control) panel the total corroded length of a scratch was measured. These measurements were then added together to obtain the total corroded length for all the test (control) panels. This sum was divided by the sum of all the test (control) scratch lengths obtaining a percentage of corroded scratch to total scratch length. The percentage for the controls was divided by the percentage for the tests, see Figure 10. If this ratio is greater than one, the control (unprotected) had a greater corroded length than the test (protected). As is apparent from Table 1, this was the case for all but the second experiment and even in that case the ratio is close to one. The six experiments summarized in Table 1 were all conducted at full power while one was conducted with 15% of full power.

Experiment number two had the worst overall performance; however, the best panel was one of the test panels that was as good as any of the best test panels in the other experiments. At this time, it is unclear what effect wiping the panels down with denatured alcohol had on the results. This procedure was adopted in an attempt to remove any oils present on the panels in an effort to encourage uniform wetting. The results from experiment six are interesting, since a significant reduction in corrosion rate was still observed after the surface currents were reduced to 15% of full power.

During the experiments there was observed support for an induction time for the following reason. At the start of each experiment, both the test and control panels began to rust, as observed visually, with the control panel showing more rust

than the test panel. After a few days, the corrosion pattern on the test panels stabilized and changed little during the rest of the experiment, while the control panels continued to corrode; a finding that is consistent with that from the salt-spray experiments discussed above. This observation lends support to the hypothesis that it is necessary for a corrosion product layer to develop on the zinc, resulting in passivation, before the Module really becomes effective.

Experiments were carried out to ascertain the impact of the Module as a function of power output (Figure 10). In these experiments, a power level of 100% corresponds to 3.6 mW. It is seen that only a weak dependence of the protection efficacy on power level exists, if any at all. This finding suggests that the efficacy saturates at low power levels (possibly as low as 0.036 mW), which in turn suggests that any optimization in performance might be found in tailoring the pulse shape rather than power level.

3.4 | Postulated mechanism of zinc activation

While the present study has provided unequivocal evidence that the electromagnetically-induced current in the galvanized steel prevents the passivation of the zinc, or activates passivated zinc, and hence allows it to continue to act as a sacrificial anode, we have not yet identified the process at the molecular level that are responsible for inhibiting zinc passivation and/or for zinc reactivation. Work is currently underway to define the mechanism, but we currently do not know, in mechanistic detail, what determines the length of the induction period. Presumably, it is related to the kinetics of breakdown of the passivated zinc surface adjacent to the exposed underlying steel or due to the time that it takes zinc to achieve polarity reversal in the absence of an induced current. We offer a tentative explanation in terms of the point defect model.[17] The defective oxide barrier layer on passive zinc, $Zn_{1+x}O_{1-y}$ is an n-type semiconductor by virtue of the excess of cation interstitials and/or oxygen vacancies as the principal point defects.[18] It is postulated that the majority of

the passive current is carried by the cation interstitials, Zn_i^{2+}, which are generated at the metal/barrier layer (m/bl) interface by injection of cations directly into the barrier layer from the metal and are anhilated at the barrier layer/solution (bl/s) interface by ejection from the barrier layer to form a zinc cation in the solution. If the electromagnetically-induced current being driven though the barrier layer is sufficiently high, the excess current may lead to the generation of cation vacancies at the barrier layer/solution interface, by ejection of cations from positions on the cation sublattice at the ZnO/solution interface into the solution, and hence some of the current may be carried by cation vacancies $V_{Zn}^{2'}$ toward the metal/barrier layer interface. If the flux of cation vacancies is sufficiently high, they may not be annihilated at the m/bl interface by injection of cations from the metal, Eq. (4):

$$Zn + V_{Zn}^{2'} \rightarrow Zn_{Zn} + v_{Zn} + 2e^-, \qquad (4)$$
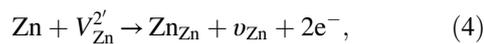
where Zn_{Zn} is a zinc cation in a normal cation position on the cation sublatice in the barrier oxide layer and v_{Zn} is a vacancy in the underlying metal, respectively. Thus, the excess cation vacancies (i.e., those that cannot be annihilated) are envisioned to condense at the m/bl interface, thereby resulting in separation of the barrier layer from the substrate metal. Accordingly, vacancy condensation results in a cessation of growth of the barrier layer into the metal via the generation of oxygen vacancies, Eq. (5):

$$Zn \rightarrow Zn_{Zn} + V_{\ddot{O}} + 2e^-, \qquad (5)$$
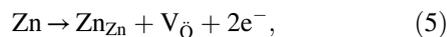
where $V_{\ddot{O}}$ is an oxygen vacancy on the anion sublattice of the barrier layer, because continued growth requires intimate contact between the oxide and the metal. However, the barrier layer continues to dissolve at the bl/s interface. Dissolution of the $Zn_{1+x}O_{1-y}$ at the bl/s interface that is unmatched by film growth at the m/bl interface eventually results in destruction of the passive film on the zinc and hence in activation of the galvanizing in its roles as a sacrificial anode in protecting the adjacent steel in the scribe. This mechanism is essentially identical to that postulated by Macdonald et al.[17] for passivity breakdown (pitting corrosion) induced by aggressive anionic species, such as chloride ion, and for general depassivation, as in electro-polishing, but it has also been postulated to be the fundamental process in electro-polishing, in which passivity breakdown occurs over macroscopic areas. In this interpretation, the induction time for reactivation of the zinc corresponds to the time that it takes for a critical concentration of cation vacancies to condense on the cation sublattice at the metal/barrier layer interface plus the time of dissolution of the barrier layer "cap" over the breakdown site. Finally, from a practical viewpoint, the Module will have no discernible effect while the zinc remains in the active state and

acts as a viable sacrificial anode, except possibly for a slightly higher or even lower zinc dissolution rate, or if both the zinc and the steel are passivated, in which case the corrosion rate is negligible. Under these circumstances, in the first case, the Module is not needed to affect corrosion control, that function being afforded by the sacrificial anode. However, if the zinc passivates and is incapable of protecting the steel, regardless of whether polarity reversal occurs, the Module is shown to reactivate the zinc and restore its function as a sacrificial anode. It is during this period that the Module acts to protect the underlying steel from corrosion. Thus, one of the key challenges in this program has been to identify the conditions that lead to zinc passivation and hence loss of sacrificial anode activity, so that the efficacy of the Module could be evaluated.

4 | SUMMARY AND CONCLUSIONS

The work described in this paper was designed to evaluate the efficacy of electromagnetically-induced surface currents in reducing the development of corrosion damage on galvanized and galvannealed steel panels and to indicate, to the extent possible, the mechanism by which protection is accomplished. The results of this study may be summarized as follows:

- Electromagnetically-induced surface currents are effective in protecting coated galvanized and galvannealed steel panels, as evidenced by a shift in the corrosion potential of the exposed steel at a scribe in the negative direction.
- The mechanism of enhanced protection appears to be that the electromagnetically-induced surface currents renders the galvanizing (a sacrificial anode) more effective as a sacrificial anode under conditions where zinc passivation occurs.
- The mechanism of protection is not that of classical, impressed current cathodic protection (ICCP). This is shown by the fact that the current or voltage applied to the panel by electromagnetic induction is in the form of a repetitive pulse and not a direct current that is employed in ICCP systems, again demonstrating a vital difference between the latter and the technology described here. Furthermore, the system does not contain an anode or a continuous electrolyte path between the area of damage and any connection to the electromagnetic Module.
- Unlike ICCP systems, electromagnetic induction is not limited to the region where a continuous electrolyte film exists between the path of application of the electrical current and the area being protected. Rather, similar to an antenna, the induced current covers the entire surface. As such, electromagnetic induction is effective in reducing the rate of corrosion over the entire surface of a complex shaped galvanized panel, such as an automobile body.

- The frequency of the applied electrical signal is sufficiently high that the *skin effect*, whereby current flow concentrates near the surface of a conductor, may become a factor in the mechanism of protection. Accordingly, the induced current is likely to be concentrated in the metal just below the passive film and hence is available for transmission across the film either as electron/hole charge carriers or as crystallographic defects upon conversion via charge transfer reactions at the bl/s interface.

- Activation of the zinc galvanizing by the electromagnetically-induced current occurs after an induction period. While the mechanistic details of the processes that determine the length of the induction time are currently not completely understood, it is postulated that the generation of cation vacancies on the oxide side of the m/bl interface, in order to carry the excess current imposed across the barrier layer, due to electromagnetic induction, results in vacancy condensation and separation of the barrier layer from the substrate metal, with the result that the barrier layer ceases to grow into the metal. However, the barrier layer continues to dissolve at the bl/s interface, with the result that the film thins and eventually ruptures, thereby activating the zinc as a sacrificial anode by exposing metallic zinc to the solution. In this manner, the electromagnetic induction is envisioned to enhance the efficacy of the galvanizing to protect the adjacent steel in the scribe by maintaining the zinc in the active state.

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